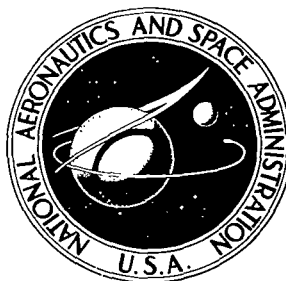


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ELECTRICITY OF CLOUDS

*by I. M. Imyanitov, Ye. V. Chubarina,
and Ya. M. Shvarts*

*"Hydrometeorological" Press,
Leningrad, 1971*



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Translation of: "Elektrichestvo oblakov."
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ANNOTATION

The electricity of the clouds substantially affects their evolution, particularly the development of thunderstorms and the formation of precipitation. The probability of lightning hitting aircraft and the reliability of the aircraft's radio communication and navigation devices are closely connected with the electricity of the clouds. In the Brobdingnagian scale of the atmosphere, as compared with the Lilliputian scale of the laboratories, our ideas developed indoors of what is possible and what isn't begin to lose sense. The case of ball lightning can be cited as an example.

At the same time, meteorologists know very little about the electrical properties of the clouds, their "electrical nature," especially modern ideas and data that are not yet published in the widely spread literature.

The booklet "Electricity of the Clouds" is an attempt to compile complete data on clouds electrical characteristics and to outline modern knowledge on the electrical properties of clouds, to describe the processes which lead to their electrification, methods devised by man to change the clouds electrical properties and to evaluate the influence of cloud electrical properties on their development

The book is designed for meteorologists and other specialists who are interested in atmospheric electricity.

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INTRODUCTION

The dependence of mankind on the weather, contrary to popular opinion, /3* increases with the development of technology and industry. The cave man was able to live even without a lightning rod. The man of the nineteenth century who erected a lightning rod on his house did not have even a remote idea of the difficulties which arise in the twentieth century, in protecting electrical transmission lines, extending for many thousands of kilometers, from thunderstorms. Even at the beginning of the present century, there was no reason to worry about the magnitude and nature of atmospheric radio noise.

The development of a new technique frequently stimulates interest in those properties of the atmosphere whose existence was not even suspected. Thus, it has become necessary to be interested in the electrical conductivity of the atmosphere and atmospheric.

There has been a considerable expansion of the characteristics of the atmosphere which meteorology must consider, monitor, measure, include in handbooks, discuss in monographs and use in weather forecasting, which encompasses a constantly expanding range of elements. The subject of the present volume — electricity of clouds — is one of these "new" areas.

Unfortunately, meteorology like any science responds with a considerable delay to the many questions that are posed. The effort to relate all elementary forces to electrical interaction, characteristic of the past century, led to the development of ideas regarding the decisive importance of electricity in clouds or the development of the latter — speculative ideas in view of the scarcity of the positive data then available. When it became clear after "electrical intoxication" that electrical forces could not explain all processes that

* Numbers in the margin indicate the pagination in the original foreign text.

took place in clouds, during the course of the "sobering up process" actually existing interactions between electrical and meteorological processes were discovered. Papers written in recent years have made it possible to get away from this extreme as well.

Studies of cloud electricity, conducted at a considerably accelerated rate, are stimulated at the present time by a number of problems which are posed both by meteorologists and by representatives of other specialties. It is possible to formulate four groups of such problems (this arrangement is still conditional):

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1. Problems directly related to the study of atmospheric electricity. These include problems such as the explanation of mechanisms of particle electrification in clouds and the electrification of clouds as a whole, and an explanation of the role of clouds in the formation of local and global electrical characteristics of the atmosphere. The first problem is also important for general physics. The second problem is still only one of the internal problems of atmospheric electricity. It is of particular significance in conjunction with work performed under the program of the atmospheric-electricity decade [175].

2. Problems related to the study of cloud physics, the study of the possibility of actively influencing processes in the clouds. These problems include a clarification of the problems of how and to what extent micro- and macro-processes in the clouds affect the electrical condition of the latter, and a determination of the role of electrical forces in the development and breakup of clouds (for example, [44, 49, 123]).

Modern investigators know that as clouds develop — although the understanding of cloud development still has not gone beyond the area of detection in the measurement region — the electrical fields and the charges in them increase. This correlation was detected recently in an effort to link the

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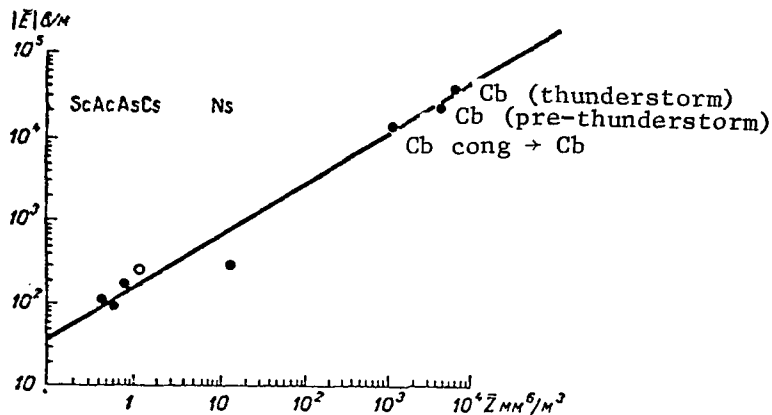


Figure 1. Relationship between the average potential gradient of the electrical field of the atmosphere $|E|$ and the average radar reflectivity \bar{Z} in clouds of different types. The small circle (o) represents the value of the reflectivity in Cs, converted to the water content with consideration of the fact that the dielectric constant of ice at the measurement frequency is approximately five times less than the permeability of water.

average field intensity $[E]$ in clouds of different types with the average radar reflection in them. Figure 1, plotted according to data on clouds observed in the zone extending from 50 to 60° N, shows that there is a relationship between $\log \bar{Z}$ and $\log |E|$ which is nearly linear [29]. It is curious that the forms of clouds on this graph are arranged in "natural" order. They were placed this way by an aerologist who decided to arrange the various clouds on a scale indicating the comparative "degree of development" of clouds from one type to another. This sequence can be explained only by the fact that the growth of a cloud electrical field accompanies an increase in the number of particles and their size, or by the fact that the electrical characteristics of clouds play an important role in the change of concentration and

the size of particles. If the first explanation is correct, the data on electrical characteristics of clouds may be valuable to meteorologist only as a means of determining the state of clouds [39, 83]. If the second explanation is correct, the study of the electrical characteristics of clouds is unnecessary even for an understanding of the physics of their development (for example, [44]).

3. Problems whose solution stimulates the development of other sciences. A basic change in the scale of the processes in nature, in comparison to those in the laboratory, may lead to detection of new physical processes and relationships. Possible examples that could be cited are the gigantic electrodeless spark discharge, lightning, and the mysterious ball lightning.

4. Problems whose solution promotes technical progress. These include problems of static electricity on aircraft and prevention of aircraft entering thunderstorm zones, and problems connected with the influence of electrical characteristics of research probes on the results of cloud characteristic measurements, etc.

The need to solve these problems increases each year. Thus, for example, the rapid increase of aircraft speed, expansion of the number of aircraft in the world and the need to fly under all meteorological conditions make it very important to solve problems of static electrification of aircraft [2] in order to increase flight safety. Information on possible damage to an aircraft by lightning must also be improved for the same purpose.

Without dwelling on other problems (including those such as a clarification of the relationship between the cloud condition and their shortwave and longwave radio emission [145, 174], whose solution is very useful in the development of satellite meteorology), we will merely note that the solutions of all of these problems are largely interrelated and are based on measurements of the macro- and micro-electrical characteristics of clouds and on concepts regarding elementary mechanisms of charging and interaction of cloud particles.

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Regardless of the importance of studying electrical characteristics of clouds, until recently there were no reliable data whatsoever on the electrical structure of clouds and their electrical characteristics. Suffice it to say, for example, that even the fundamental work of Wilson [170] and Frenkel' [9] in the field of electrical characteristics of clouds were based on highly arbitrary assumptions regarding the strength of electrical fields in clouds, charges in them, etc. Even now, the conductivity values that exist in thunderstorm clouds, for example, employed by various authors, differ by several orders of magnitude [5, 116], while the strengths and charges of the fields in them differ by an order of magnitude [51, 116, 140].

The concept of "electrical characteristics of a cloud" includes the density of the electrical space charge, the potential gradient (strength) of the electrical field, the electrical conductivity of the air in the cloud and in its vicinity, the spectral density of the electric charges on the cloud and precipitation particles, the spectral density of the ions in the cloud air, and the density of the electrical current running through the cloud and near it. Some of these characteristics are basic; others are arbitrary. Thus, on the basis of the distribution of the potential gradient of the electrical field in the cloud and its vicinity, we can determine how the density of the space charge is distributed (the first value is more easily measured). On the basis of the distribution of the potential gradient, the electrical conductivity of the air, and the field of air movement velocities, it is possible to calculate the distribution of the total electrical current density of the atmosphere. Unfortunately, we are only at the beginning of the road, as far as understanding cloud electricity is concerned.

Only recently, by means of direct measurement in clouds, was it possible to obtain an idea of how the electrical fields in them are distributed, to partly systematize these data, and also to obtain some new information regarding the distribution of charges on cloud particles and the precipitation particles, as well as the electrical conductivity of the air within the clouds.

Calculations of the properties of clouds on the basis of data from ground measurements have not led (and — as has now become clear — could not have led) to correct results. It is still impossible to forecast electrical characteristics, since we lack sufficiently complete data regarding the physical processes of charging of individual cloud particles and the entire cloud as a whole. In recent years, a considerable step forward has been made in theoretical and experimental studies of the interaction of cloud particles. Studies of the elementary mechanisms of particle charging are much fewer, but are still going forward. /7

The data which have been obtained are concentrated primarily in articles which deal with certain details, and therefore only specialists read them. The present booklet is designed to serve as an aid in breaching the gap between the concepts of narrow specialists regarding atmospheric electricity and the concepts of specialists in other, admittedly related areas regarding cloud electricity. Such a gap unavoidably develops in the development of any science, but it is particularly serious when the interaction of the sciences — let us say, of atmospheric electricity and cloud physics or atmospheric electricity and electrochemistry, etc. — is required for solving the basic problems mentioned in the introduction.

We will begin with a presentation of the actual material which we have available regarding cloud electricity. The significance of this material for the solution of the diverse problems mentioned above will become clear as the data are presented in the following chapters.

CHAPTER I

ELECTRICAL CHARACTERISTICS OF CLOUDS

§ 1. Electricity in Stratiform Clouds

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The most extensive studies of the electrical structure of stratiform clouds have been performed in the USSR. The overwhelming majority of data regarding the vertical component of the potential gradient E of the electrical field of the atmosphere in clouds have been collected during vertical soundings of the atmosphere. The results of measurements of E have been averaged vertically for a layer 100 m thick. The aircraft usually travels in a spiral as it rises to make the sounding, with the average horizontal velocity of the aircraft being approximately 50-60 m/sec and the vertical rate of climb being 4-5 m/sec. Hence, when averaging the field over 100 m along the vertical, there is simultaneous averaging along the horizontal for a path about 3 - 4 km long, with the average along the horizontal increasing with altitude, since the rate of climb decreases at high altitudes.

At the present time, it has become possible to generalize these data [45]. It has been found that the combination of absolute values of \bar{E} in the clouds may be approximated satisfactorily by a logarithmically normal distribution (Figure 1.1). The parameters of this distribution are quite different for various clouds (Table 1.1).

In Table 1.1, on Graph No. 1, we have presented the results of measurements made in the vicinity of Leningrad, in No. 2 in the Kiev area,

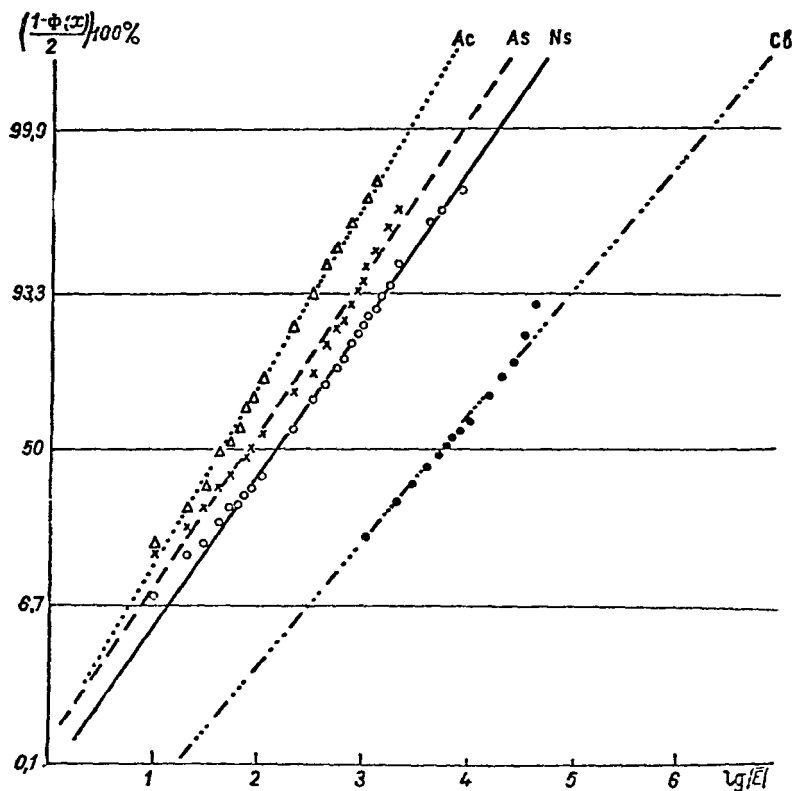


Figure 1.1. Distribution of absolute values of the potential gradient of electrical field in Ac, As, Ns, and Cb clouds, represented on a logarithmic-probability grid.

No. 3 in the vicinity of Tashkent. The values $|E|_{\max}$ shown here and in Table 1.1 represent a calculated value of $|E|$ which is encountered with a probability of less than 0.1%. The actually recorded limiting values of $|E|$ in St and Sc clouds are approximately $2-3 \cdot 10^3$ V/m; Ac, approximately $5 \cdot 10^3$ V/m; As, approximately $20 \cdot 10^3$ V/m; Ns, approximately $40 \cdot 10^3$ V/m; Cb, approximately $280 \cdot 10^3$ V/m.

TABLE 1.1. CHARACTERISTICS OF THE DISTRIBUTION OF THE
ELECTRIC FIELD STRENGTHS IN VARIOUS CLOUDS

Type of cloud	Average thickness m			$ E _{AV \cdot arith}$ V/m			$ E _{med}$ V/m			$ E _{max} \cdot 10^3$ V/m			σ dB		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
St	450	450	400	160	160	160	100	120	130	2	1.5	1	8	7.5	6
Sc	500	400	450	130	160	160	80	100	100	2	2.5	7.5	9	9	12
Ac	500	500	600	100	180	250	40	80	70	2.5	1.5	4.6	11	12	17
As	1300	1000	1300	200	320	160	100	150	350	8	7.5	60	13	11	14.5
Ns	2700	2200	2200	300	450	700	150	250	500	16	7.5	135	13	10.5	16.5
Cb							5000			2000			17		

TABLE 1.2. DISTRIBUTION CHARACTERISTICS $|E|_*$, AVERAGED OVER THE
ENTIRE CLOUD

Type of cloud	$ E _*$ V/m	$ E _*$ 10^3 V/m	σ dB
St	150	2	7
Sc	100	1.7	6
Ac	60	2.5	10.5
As	130	7	11.5
Ns	250	10	11

As we can see from Table 1.1, the average values of $|E|$ in clouds in the indicated measurement areas are relatively similar, and there is a somewhat greater difference in the dispersion, while the extremal values of $|E|$ are still more different. The extremal values are especially high in clouds which produce precipitation. The values of $|E|_{max}$ in As and Ns in the southern regions approach 10^5 V/m.

The correctness of this extrapolation is supported by the fact that aircraft-laboratories have recorded values for the potential gradient of the electrical field of the atmosphere which are in excess of $40 \cdot 10^3$ V/m, and by the fact that aircraft have been damaged by lightning in such clouds. In the latter case, it may be correctly suggested that in stratiform clouds (As, Ns) $|E|$ has reached values that are characteristic of thunderstorm clouds, i.e., has exceeded 10^5 V/m.

It is important to note that the average potential gradients in individual clouds may differ considerably from those presented in Table 1.1. In

Table 1.2, we have listed the distribution parameters of $E_{av}/*$ — the potential gradient of the electrical field, averaged over the entire cloud — for clouds of different types on the basis of measurement data collected in the vicinity of Leningrad. In other words, this table shows how much one cloud can differ from another on the average. From a comparison of Tables 1.1 and 1.2, we can conclude that the distributions of the values of $E/*$ averaged over the entire cloud and the distributions of $E/$ averaged over 100 meter-layers do not differ markedly from one another. The similarity of the two distributions is linked either to the random nature of the selection and the relatively small size of the cloud volume that was sounded, or to the fact that the distributions that were obtained (Tables 1.1 and 1.2) characterize essentially the difference between the electrical state of one cloud and that of another (in one there are strong electrical fields, while those in the other are weak). Within one cloud, the probability of finding both very large and very small values of $E/$ is indicated by the curve showing the distribution of the electrical inhomogeneity in the clouds (see Figure 1.5), about which we shall speak later. On the basis of the experiment, we can state that σ for the distribution of $E/$ within one cloud may be considerably less than the average given in Tables 1.1 and 1.2, and amount to 1.5-2 dB, but in some clouds (especially rain clouds) it may be of the same order as in Tables 1.1 and 1.2, and even higher.

Let us note some of the general features of electrical characteristics of these types of clouds. The electrical activity of the clouds, characterized in our case by the average absolute values of the electric field strength in them, increases from one type of cloud to the next in approximately the following order: St, Sc, Ac, As, Ns, Cb. /11

As a rule, the electrical activity of the cloud (Figure 1.2) increases with increasing cloud thickness (d) and the extremal values of the potential gradients of the fields in the clouds increase particularly markedly. This is worthy of attention. The dependence of the cloud electrical activity on thickness shows up much more clearly in southern latitudes than in northern

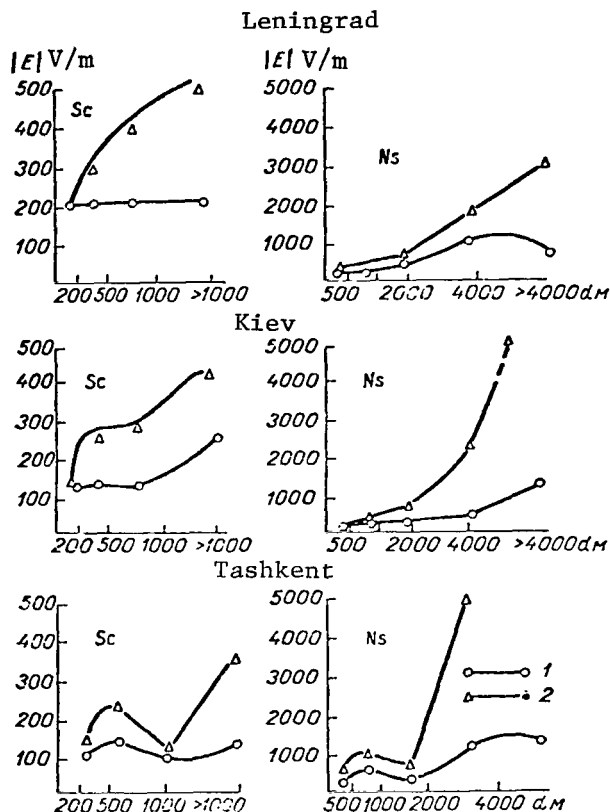


Figure 1.2. Average ($\overline{|E|}_{av}$ - curve No. 1) and maximum ($|E|_{max}$ - curve No. 2)

potential gradient of electrical field as a function of the thickness (d) of the cloud.

ones [3]. The electrical activity of clouds increases on the average from northern latitudes toward southern ones. This may be related to a change in the microphysical characteristics of the clouds with latitude. The electrical characteristics of clouds change from winter to summer, as has already been pointed out in [3]. Usually, in winter the average and maximum values of the potential gradient of electrical fields E as well as the differences in potentials at the cloud boundaries are less than in summer. On the basis of measurements of E , it has been possible to determine the typical vertical electrical structures of clouds. For purposes of classification by type, and also in order to compare the electrical structures, the distribution curves with altitude for the value of E in clouds have been calculated for relative altitudes D/D_0 , where D_0 is the cloud thickness. Rain clouds are divided into parts which are located above the level of the zero isotherm and below it.

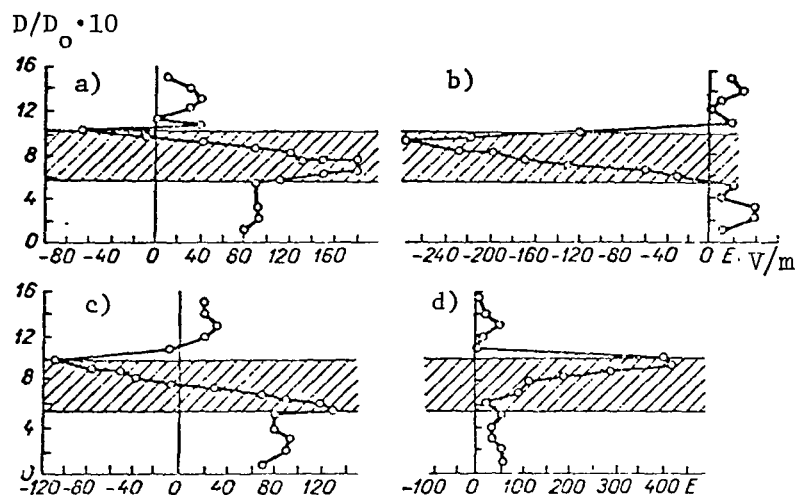


Figure 1.3. The potential gradient of electrical field E as a function of reduced altitude D/D_0 in stratocumulus clouds with a specific type of electrical structure and in the absence of clouds of other types (Leningrad, 1958-1959).

Polarized clouds: a - positively (72 cases);
b - negatively (20 cases);
Charged clouds: c - positively (38 cases);
d - negatively (10 cases).

In Figure 1.3, as an example, we have plotted four characteristic electrical structures which are encountered in warm stratus clouds at middle latitudes [3]. There are positively polarized clouds (+) which have a positive charge in the upper part and a negative charge in the lower part, negatively polarized clouds (-) whose charges are arranged in the opposite fashion, and singly charged clouds [both positively (+) and negatively (-)]. Clouds of limited thickness are usually singly charged. As a rule, thick clouds are multicharged. This statement is illustrated in Table 1.3. However, a similar

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TABLE 1.3. AVERAGE THICKNESS (m) OF CLOUDS OF DIFFERENT TYPES FOR VARIOUS ELECTRICAL STRUCTURES, LENINGRAD, 1958-1959

Type of cloud	Singly charged clouds		Doubly charged clouds		Multi-charged clouds
	+	-	±	≡	
St	200	200	450	450	700
Sc	260	250	400	450	700
As	650	700	800	900	1500
Ns	650	700	950	1600	2000

type of structure has been obtained for clouds of other types. It is important that many of these structures cannot be explained by viewing the clouds as passive resistances included in the electrical circuit of the ionosphere and the ground. In all probability, many clouds (even those without precipitation) act as electricity generators. A similar characteristic of thick fogs has been determined earlier in [69, 118].

Figure 1.4 shows the distribution of the potential gradient of an electrical field E with altitude in nimbostratus clouds with a mixed phase structure, observed at middle latitudes. The maximum values of $|E|$ are observed in clouds of mixed structure, especially in the zone between the 0-10°C isotherms; in this zone, there is an intensive separation of charges. Beneath the cloud or in the lower part of it, one often finds areas of positive charges that are associated with precipitation. Let us recall once again that both the average and the extremal values of E in such clouds are higher than in clouds of the other types discussed. One finds both positively (Figure 1.4) as well as negatively polarized clouds [3].

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On the basis of the results of measuring the potential gradient of the electrical field of the atmosphere, it is possible to calculate, by using the Poisson equation, the density distribution ρ of space charges in the clouds.

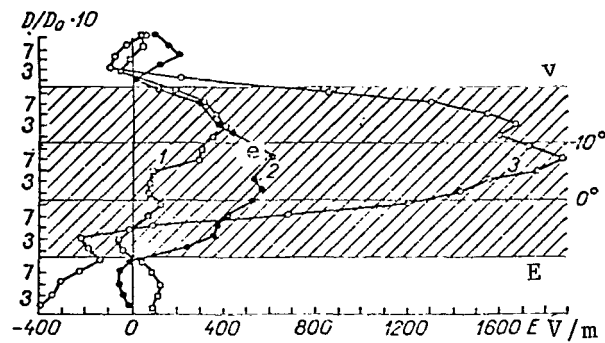


Figure 1.4. Reduced path of potential gradient E of electrical field in Ns clouds with a mixed structure.

1 - Leningrad, 1960-1962 (18 cases); 2 - Kiev, 1960-1963 (7 cases); 3 - Tashkent, 1960-1961 (10 cases); E and v - lower and upper limits of the clouds.

On the average, the density ρ of space charges in stratus and stratocumulus clouds is on the order of 10^{-11} k/m³ (Table 1.4).

TABLE 1.4. * RECURRENCE (%) OF THE DENSITY VALUES OF SPACE CHARGES IN Sc AND Ns CLOUDS

$\rho \cdot 10^{11}$ k/m ³	0.01-0.34	0.35-0.69	0.70-1.0	1.01-1.35	1.36-1.69	1.70-2.0	2.01-2.35	2.36-2.69	2.70-3.0	3.01-3.35	3.36-3.69
Sc	52	22	9	3	2	2.5	2.5	1	1	1	4
Ns	35	16	7.5	4	4	3	2	2.5	2	4.5	19.5

Horizontal electrical inhomogenities in clouds of these types are comparatively small. The extent of the zones where the potential gradient changes by no more than 20 - 30% of the average value ranges from 200-600 m.

Considerable inhomogeneities of E — reaching, let us say, up to 100% are rarely found. Electrical inhomogeneities in clouds are calculated as the ratio of ΔE deviations from the average potential gradient of the electrical field in the selected area of the horizontal path to the average value $|\Delta E/E_{av}|$. The distribution of the values of the electrical inhomogeneities in clouds is expressed quite well by a normal logarithmic distribution. Figure 1.5 shows that the median values of the inhomogeneities in the various forms of clouds are similar, and amount to about 20%. However, the slope of the curves differs, indicating a different probability of encountering considerable inhomogeneities in clouds of different types.

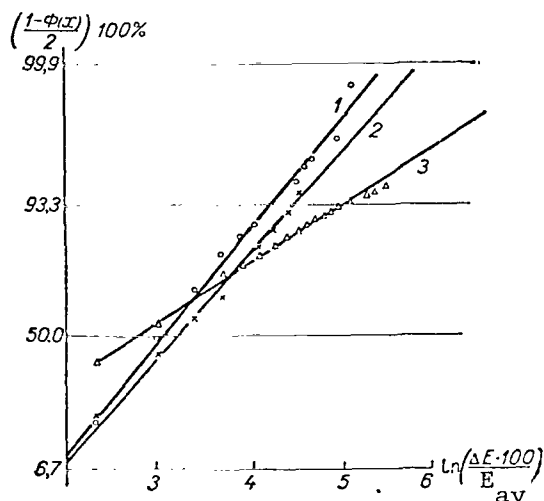


Figure 1.5. Distribution of values of electrical inhomogeneities $\Delta E \cdot 100 E_{av}$ in clouds of different types, plotted on a normal logarithmic grid.
1 - Ns; 2 - Sc; 3 - Cb.

In Table 1.5, we have presented the values $|\Delta E/E_{av}|_{med}$ and the calculated values $|\Delta E/E_{av}|_{max}$, corresponding to an encountering probability less than 0.1%. Hence, if we find deviations from the average value of E by 300% in Sc and Ns once out of 1000 inhomogeneities, we will find deviations from the average values by 1500% in Cb in one case out of a thousand. The inhomogeneities occupy 50-60% of the flight trajectory in Sc, and 70-80% in Ns. The average density of the space charge in inhomogeneities for St and Sc clouds differs insignificantly from the average density of the space charge calculated for the

entire cloud, with higher values for the density of the space charges encountered in smaller zones.

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TABLE 1.5.

Type of clouds	$ \Delta E/E _{\text{av/med}}\%$	$ \Delta E/E _{\text{av/max}}\%$
Sc	25	350
Ns	22	300
Cb	17	1500

The density of the space charge in Ns may be significant. Thus, in Ns we find values of ρ on the order of 10^{-10} C/m^3 , and even 10^{-9} C/m^3 . The probability of the appearance of $|\rho|$ of different density in nimbostratus clouds is shown in Table 1.4.

In Figure 1.6, we have plotted the curves for the recurrence of the dimensions of the electrical inhomogeneity zones in clear weather, and in clouds of different types. It is interesting that the dimensions of the zones of inhomogeneity are smaller in clouds than in clear weather, and in clouds which are more active (Ns) the inhomogeneity zones are smaller than in Sc. Thus, in clear weather one most often encounters zones measuring from 100 to 500 m, in Sc — from 50 to 400 m, and in Ns — from 50 to 200 m. It is necessary to keep the fact in mind that these dimensions of the inhomogeneities are linked in a certain fashion with the measurement method. Inhomogeneities are detected if the measured element in them (in this case E) differs by more than several percent from the average value of the element in the measurement area. As the inhomogeneity dimension in this case, we have adopted the distance between adjacent extrema of the field. /16

In their papers, foreign investigators present individual data on measurements of the electrical field intensity in clouds of these types. Therefore, we cannot speak of any kind of systematization of foreign data. In an attempt to transfer the data on E presented in a pamphlet, as obtained by I. M. Imyanitov and Ye. V. Chubarina, to other geographic regions or to use them for calculating some processes taking place in these regions, it is necessary to keep in mind the relationship (shown for example in Table 1.1 and mentioned in the text) of the average parameters of E to the physical, geographic conditions of cloud formation.

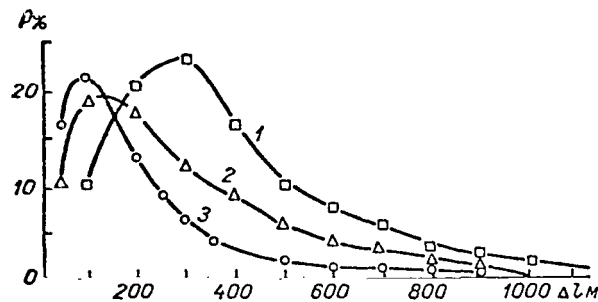


Figure 1.6. Recurrence of sizes of zones of electrical homogeneities.

1 - in clear weather; 2 - in Sc; 3 - in Ns.

In measurements of the potential gradient E of the electrical field of the atmosphere, carried out for a relatively long period of time in the mountains at altitudes at which cloud formation takes place [77, 141], variability of E in clouds and in their vicinity was observed less than in the aircraft studies of I. Imyanitov and Ye.V. Chubarina. The absence of sufficient information regarding the quantity and method of analyzing the material presented by the investigators [77, 141] does not give us any idea of the cause of the differences, but the possibility cannot be excluded that the considerable similarity /17 of the electrical fields has something to do with the specific conditions of cloud formation under mountainous conditions.

The establishment of relationships between the microphysical characteristics and the potential gradient E of the electrical field in the clouds is of considerable interest in conjunction with a search for the causative relationships between the parameters characterizing the development of clouds and their electrical characteristics.

Unfortunately, we do not have sufficiently reliable and unanimous results in this connection. To support the fact that a relationship between the microphysical and electrical characteristics of a cloud does exist, we can use Figure 1. Direct simultaneous measurement of water content, microstructure and electrical parameters in stratiform clouds are very few in number, and their results are not in agreement.

An important electrical characteristic of clouds is the electrical conductivity of the air in them. The electrical conductivity in the clouds must be less than in the free atmosphere, due to the capture of ions by the drops.

Measurement of electrical conductivity of the air in clouds is a complicated task, since it is necessary to solve many difficult methodological problems, and we will not dwell on this topic (for example [1, 31, 85]). It is obvious why only a few such measurements have been made. As a rule, the measurements are performed with the aid of an inertial apparatus. Nothing is known regarding the characteristics of the change in electrical conductivity in the air in individual portions of clouds.

Judging by the results of measurements, the values of polar conductivity in clouds are roughly equal. Judging by the data of Alley and Phillips [92], electrical conductivity in clouds decreases by a factor of 3 to 5, and in some cases by a factor of 20, in comparison to the electrical conductivity in purely atmospheric air at the same level. According to the data of N. Krasnogorskaya, it decreases by approximately a factor of 3 [57]. Zachek [32], who carried out the first aircraft measurements of electrical conductivity of the air in thin St and Sc clouds by means of an apparatus which reduced the effect of basic sources of error in measuring electrical conductivity in clouds, also found a reduction of electrical conductivity in comparison to the values in pure air by a factor of 3 to 25.

Using an improved apparatus of the type described in [33], equipped with an inertial filter, attempts were made to measure the electrical conductivity of the air from an aircraft in dense St and Sc clouds as well as As and Ns [30]. However, these attempts have as yet been unsuccessful due to the considerable charging of the measuring electrodes of the apparatus when struck by droplets, and the discharging of the electrodes when the droplets separate from them. It is not clear to what extent this source of error may have affected the measurement results in the cited works.

/18

The electrical conductivity of the air in nimbostratus clouds has not been investigated in detail. However, in a work by N. Krasnogorskaya [57] in which the data of extensive measurements of air electrical conductivity on Mount Elbrus are analyzed, there are no unusual features in the pattern of electrical conductivity associated with the passage of rain clouds. We can, therefore, assume that electrical conductivity in these clouds was the same as in stratus clouds, i.e., somewhat less than the electrical conductivity in the free atmosphere at the same level. It is necessary to point out, however, that in [57] the influence of electrode charging on the measurement results was not taken into account.

Let us consider the electrical microphysical characteristics of stratus, stratocumulus, and nimbostratus clouds. The charges of individual droplets have been investigated by several authors [92, 138, 163, 164, 58, 18, 68]. Summaries of the results of measurements are presented in [56, 68]. Data selected from them and supplemented by data from [58, 18] are represented in Table 1.6.

It is apparent from Table 1.6 that the results of measurements performed by different methods in clouds formed in various geographical regions under different conditions differ quite markedly from one another, even in clouds of similar types. The reasons for this have not yet been investigated, but we cannot exclude the possibility that the difference is caused by various conditions of cloud formation, as well as by their different rates of growth.

The experiments of Alley, Phillips and Kinzer [92, 138], for example, were performed in "young" clouds.

Relatively similar results were obtained by A. Katsyka, G. Petrov and Chiao Bo-lin [56] for clouds, and by L. Makhotkin, V. Solov'yev [68] and M. Akimov [18] for fogs. According to their data, positively and negatively charged droplets are encountered with approximately equal probability. The measured charges were found to be approximately proportional to their radius $q = kr$.

If r is expressed in microns and q in electrical charges, $k = 10^{-20}$. The difference of the spectrum of the particle charges in zones of inhomogeneity from the average spectrum was not determined.

Data on the charge on small cloud droplets in clouds producing precipitation are included in Twomey's work [163]. He detected a rather significant, overwhelmingly positive charging of the droplets in warm clouds and (with approximately the same magnitude) predominantly negative charging of the droplets in clouds containing the solid phase. He explained the latter effect by negative charging of the growing ice particles when they collided with supercooled droplets [14]. It is necessary to perform additional studies in order to get a clear idea of the intensity of fine particle charging in nimbostratus clouds. Obviously, it can be significant. The charge on individual precipitation particles falling from nimbostratus clouds, according to measurements made at the surface of the Earth, is equal to $3 \cdot 10^{-14} - 3 \cdot 10^{-13}$ [5, 19, 84]. With a concentration of approximately 100 particles per m^3 and a precipitation rate of approximately 1 mm per second, we could expect that the current density of the clouds would reach $10^{-9} - 10^{-10} A/m^2$. However, the precipitation currents from nimbostratus clouds at middle latitudes are equal only to $5 \cdot 10^{-12} - 5 \cdot 10^{-11} A/m^2$ [5]. This has to do with the fact that the number of positively charged droplets is nearly equal to the number of negatively charged particles and, as was noted by Ye. Federov [84], the values of the

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TABLE 1.6. AVERAGE DROPLET CHARGE (ABSOLUTE VALUES) IN ELEMENTARY CHARGES (1 ELEMENTARY CHARGE APPROXIMATELY EQUALS $1.6 \cdot 10^{-19}$ C)

Source	Measurement conditions	Details of measurement	Radius of droplets, microns			
			2	5	8	10
[56]	Fogs	a	20	74	(42)	(46)
		b	18	67	(20)	(20)
[18]	Fogs	a, i	28	59	94	(73)
[56]	St and Sc	Slope of Elbrus				
		(d	19	48	-	-
		a, g (e	28	68	81	104
[56]	St and Sc	Aircraft measurements				
		a, f	25	94	127	88
[56]	St and Sc	Aerostatic measurements				
		a, g	36	96	-	-
[58]	Sc, warm	Aircraft measurements				
		(j	90	100	-	-
		a, f, i (k	230	700	-	-
[92]	Orographic	Mountains (California)				
[138]	St and Sc	b, l	5	7	9	10
[163]	St and Sc warm and supercooled	Mountains (Tasmania)				
		n	-	200	800	1200
[138]	Cb with thunderstorms	Mountains (California)	-	270	320	-

Notes: a - droplets with measureable charges; b - all droplets; d - slightly electrified clouds; e - highly electrified clouds; f - device of G. Petrov [74]; g - device of A. Sergiyeva (Katsyka) [81]; j - zones where there was equiprobable existence of charged droplets of both polarities; k - zones where droplets were charged primarily negatively; l - results of measurements [92, 138] summarized in [56]; m - small number of measurements; n - clouds with precipitation and without precipitation.

average and maximum charges of the positively and negatively charged droplets increase and decrease simultaneously, i.e., the precipitation does not remove much of a charge even in individual parts of the cloud.

The charges on precipitation particles in southern latitudes are greater than those given by T. Takahashi and K. Isono [157]. For example, the maximum value for the charge on drops of rain at the surface of the Earth and in clouds was found to be approximately $3 \cdot 10^{-12}$ C. The current density of the precipitation from stratus clouds is higher in southern latitudes [151]. Obviously, both the charges and the field in the clouds in southern latitudes must be higher than in clouds of middle latitudes⁽¹⁾.

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It should be pointed out that if the data on the electrical field intensity, space charges, electrical conductivity of the air and charges on the particles, including the precipitation particles, in clouds were added for the last 10 to 20 years, data on the magnitude of the precipitation currents will be seen to have increased since the end of the last century. These measurements have not contributed much to the knowledge of the electrical structure of clouds. According to the data on precipitation currents, even with application of these terrestrial measurements of the electrical field, it has not been possible to establish the electrical structure of the clouds with sufficient completeness, although unquestionably, in many cases involving non-thunderstorm clouds, the falling precipitation current may determine the total electrification of the clouds (see, for example, [137]). The estimates of Wilson [170], which showed that not only the magnitude of the charge but also the sign can change when drops of precipitation fall from a cloud, explained the ineffectiveness of attempts at terrestrial measurement of the charge and the current of the droplets to restore the processes taking place in the cloud.

(1) The transposition of data on electric currents above thunderstorm clouds derived over a limited region to the entire globe, with all ensuing consequences, and absolutization of measurements for clouds developing under very specific mountain conditions will serve as an illustration as to how much extrapolation of any special data on specific clouds for the properties of clouds of all types has become a routine procedure in atmospheric electricity [141].

Measurements [42] made directly beneath As and Cs from which precipitation was falling showed that the precipitation particle charge in the clouds may be on the order of 10^{-11} C.

According to data on the electric field intensity, electrical conductivity of the air λ and the exchange coefficient k , we can estimate the total electrical current of the "leakage" of charges from the cloud electric dipole. The current density j is made up of the density of the conductivity current λE and the density of the current of turbulent diffusion $k/4\pi \cdot \partial^2 E / \partial z^2$, where z is the vertical coordinate. For As and Ns clouds, the current density of conductivity is on the order of 10^{-11} A/m², while the current density of diffusion is of the same order or even less. Hence, the internal current density of the "leakage" of cloud charges in nimbostratus clouds will not exceed several units, 10^{-11} A/m². In individual clouds, this value may be significantly higher.

As follows from the data presented in this section, the results of measuring the electrical field in clouds and the data derived from these results concerning the distribution of the space charge in clouds are generalized to a certain extent and for a certain geographical region. Data on other electrical characteristics have a fragmentary nature to a large extent.

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§ 2. Electricity of Convective Clouds Without Rain

The electrical structure of convective clouds without rain was established on the basis of studies at moderate latitudes of approximately 140 large cumulus clouds ranging in height from 1500 to 4000 m [85], as well as ordinary cumulus clouds [34].

The electrical structure of a convective cloud is shown in schematic form in Figure 1.7. Cumulus congestus clouds, like cumulus clouds, contain two basic charges. At the top, as a rule (75% of the cases), is the positive charge, which takes up the entire upper part of the cloud, while the negative

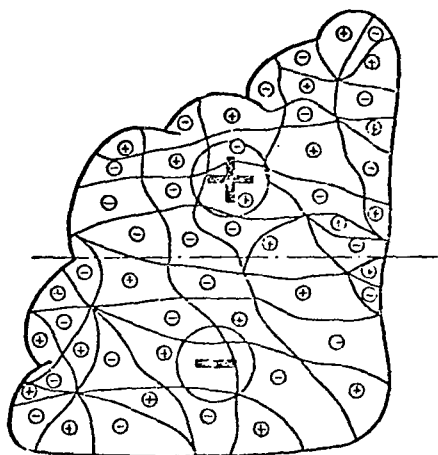


Figure 1.7. Electrical structure of a convective cloud.

charge is at the bottom. The average space charge density ρ in these areas is small; in 50% of the cases it amounts to $3 \cdot 10^{-12} - 6 \cdot 10^{-11} \text{ C/m}^3$, but cases have been found in which $\rho > 3 \cdot 10^{-10} \text{ C/m}^3$. The potential gradient E of the electric field in the clouds, formed by the average distributions of the space charges, in 50% of the cases does not exceed $+500 \text{ V/m}$, but sometimes can exceed several thousands of volts per meter. In cumulus (Cu), approximately the same field values are found. Against the background of these basic, relatively low space charges, negative and positive space charges of high density are located chaotically in the cloud. In 75% of the cases, these

charges exceed $6 \cdot 10^{-11} \text{ C/m}^2$. Space charges have been found which reach up to $3 \text{ to } 7 \cdot 10^9 \text{ C/m}^2$; areas occupied by the charges extend, it is true, no more than 50 m. On the average, zones of extremal charges have dimensions ranging from tens to hundreds of meters. The most probable size for zones of inhomogeneity is about 150 m (Figure 1.8). The distribution of the sizes of these zones is satisfactorily described by a normal logarithmic law [41]. High charges are usually associated with small zones. The potential gradient E in these zones exceeds 1000 V/m in 50% of the cases, exceeds $10,000 \text{ V/m}$ in 2% of the cases, and is more than $20,000 \text{ V/m}$ in 0.1% of the cases (according to data from extrapolation of the distribution curve).

The spectrum of the sizes of the inhomogeneity zones is very similar to the spectrum of the zone dimensions where the electrical charge of the aircraft changes, as well as the spectrum of the flows in convective clouds, determined on the basis of data from an aircraft accelerometer and a low-inertia

/22

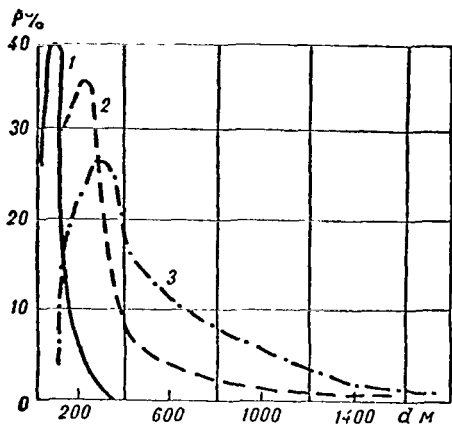


Figure 1.8. Recurrence of zone sizes with extremal charges in cumulus congestus clouds (1), thunderstorm clouds in stages of ripeness (2) and decay (3).

thermometer [35]. In these same zones, as indicated by measurements of an aircraft electrical charge made as early as 1954-1955, the value of which increases with an increase in the number of cloud particles, there can be a highly significant change in the concentration and size of the cloud particles. G. Petrov [75] notes in particular the existence of areas of similarly charged particles, while N. Vul'fson and A. Laktionov [28] have demonstrated the existence of areas with drop radii greater than nine microns against a background of "voids" where these drops do not exist.

There is no noticeable increase in the density of the space charges in cumulus and cumulus congestus clouds as they develop. In clouds which exist for longer than 1000 seconds, these space charges can be seen. The rate of space charge accumulation reaches $3 \cdot 10^{-15}$ to $3 \cdot 10^{-13}$ C/m³ per second [35].

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The electrical conductivity λ in cumulus clouds is measured episodically near the ground [92]. Individual aircraft measurements have also been performed of the electrical conductivity of the air in slightly developed cumulus clouds [30]. The inertia of the apparatus has made it possible to estimate it only as an average value. On the average, the electrical conductivity in Cu is several times less than the electrical conductivity in a pure atmosphere. Measurements of λ in Cu are subject to the same measurement errors as in stratus clouds.

The drop charges in cumulus clouds are at least the same as those in stratiform clouds (see Table 1.6), but we do not have more complete data on the charge of the particles in them.

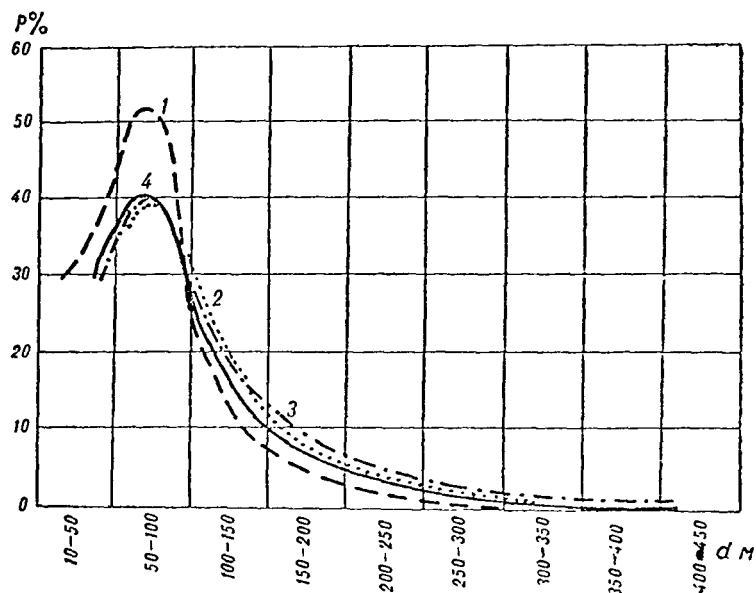


Figure 1.9. Recurrence of linear dimensions of air flows (1), zones of extrema of aircraft charges (2), field intensity (3) and temperature (4).

Since the gradient of average density of space charges in cumulus congestus clouds is of the same order of magnitude as in nimbostratus clouds, while the exchange coefficient in the former is one order higher than in the latter, the leakage current of the "cloud generator", which is linked (in addition to the electrical conductivity of the air) to the turbulent movements in clouds, will be one order of magnitude higher in cumulus and cumulus congestus clouds than in nimbostratus. On the average, they may be estimated to be 10^{-10} A/m². General observations of the electrical measurements in stratus clouds (Section 1) are almost completely devoted to the results of measurements in cumulus clouds.

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§ 3. Electricity of Cumulonimbus Clouds

Studies of the electrical structure of thunderstorm clouds began long before the development of methods to measure the electrical field intensity of the atmosphere aboard aircraft. The results of these studies, obtained on the basis of measurements of the field intensity distribution in clouds by means of sondes and changes in the potential gradient of the electrical field of the atmosphere at the surface of the earth, are generally well-known. They have been presented in a number of monographs, for example in [74].

In general, the electric structure of cumulonimbus clouds largely resembles the picture shown in Figure 1.7. However, the basic charges in them are great and very distinct in comparison to the charges in Cu congestus. The difference lies in the presence of a third, low area of positive charges connected with the rain area. In this regard, they have a certain formal similarity to stratonimbus clouds.

The arrangement of basic charges in thunderstorm clouds is obviously similar to that obtained by Simpson et al. [149, 150].

Workman writes: "It appears most likely that the electrical charges are formed in the area from -5° and possibly up to -20°C , and that the initial process of charge separation takes place from the -5°C level to the very top of the cloud. Generally speaking, there is an area of relatively concentrated negative charges which extends upward for 1-2 km and even further in isolated cases. Approximately 1-7 km above this region is an area of more diffuse positive charges." [27].

Real clouds (even in a schematic representation) may differ significantly from the classical model in Figure 1.10. In addition to the characteristic feature of cumulus clouds — the existence of numerous areas of "secondary"

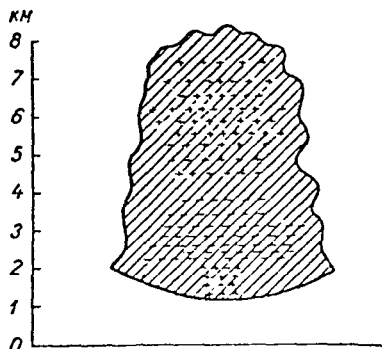


Figure 1.10. Electrical structure of thunderstorm clouds.

(both positive and negative) charges, which are smaller than the basic charges — it should also be pointed out that under various physical geographic conditions the average basic charges of the clouds may differ considerably. The structure of a thunderstorm cloud may change markedly in the course of its development. Clouds are found whose polarization is opposite to that shown in Figure 1.10.

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Let us examine these features of the clouds in greater detail. Table 1.7 shows data on the more or less typical electrical structure of thunderstorm clouds⁽²⁾ obtained by different authors on the basis of ground and aircraft observations.

TABLE 1.7. ELECTRICAL STRUCTURE OF THUNDERSTORM CLOUDS

Latitude, degrees	Average electrical moment of the cloud, C. km	Charge on cloud, C	Distance between basic charges, km	Source
60—50 N.	35	23	1,5	[116]
50 N.	72	24	3	[149]
35 N.	234	39	6	[107]
35 S.	200	40	5	[127]

(2) Although classical aerology combines rain and thunderstorm clouds under the general heading of "cumulonimbus", in atmospheric electricity (whose methods readily separate thunderstorm clouds from the mass of cumulonimbus clouds) a differentiation is made between these two different forms. The development of an observation method will make it possible for all meteorologists to differentiate thunderstorm clouds from rain clouds, and so we are using different names for these types of clouds.

In the third line of Table 1.7, we have included the data by O. Gish and G. White. Characteristic of these data is the fact that they were obtained from results of measuring the vertical component of the potential gradient of the atmospheric electrical field above thunderstorm clouds. In contrast to the direct calculation of cloud electrical charges on the basis of measurement data of E within them, used for plotting the electrical structure of stratus clouds, here the charge distribution was calculated from data on the measurement of E during the flight of an aircraft above a thunderstorm cloud. Problems of this kind, generally speaking, are incorrect problems. The situation is complicated by the fact that the medium in which the space charges are located is a conductor, so that its electrical conductivity is not constant. In order to calculate the value and the distribution of the basic charges of the cloud, the authors had to establish the number of charges and the altitude at which these charges are located. The electrical conductivity of the medium was also not taken into account. /26

Extensive measurements of the potential gradient of the electrical field of the atmosphere above thunderstorm clouds have been performed in the USSR. A total of approximately 300 clouds were studied. Due to the fact that three components of the potential gradient were measured simultaneously (in a Cartesian coordinate system linked with the aircraft), it was possible to determine also the basic cloud charges and their position, assuming that their number was equal to two. The averaged results of the calculation are presented in the first line of Table 1.7. It must be kept in mind that the basic charges of the individual clouds in this region may differ by one order of magnitude from those given in Table 1.7.

Due to the fact that the aircraft made a number of successive passes over the top of the same cloud, we were able to establish that, as the cloud developed, the electrical structure of the latter undergoes considerable change [5]. Many cases were observed when in the first stage (cloud development) the potential gradients above the top of the cloud were positive, and only at the beginning of the second stage (the stage of maturity) was there a

shift to negative gradients, i.e., the cloud assumed an electrical structure like the one which is usually given in the literature. It still remains to be determined whether or not this type of change in cloud polarity in the course of development is typical of all thunderstorm clouds in the middle latitudes or whether this is a characteristic of the majority of clouds at any latitude. The change of the field direction with time above the cloud may be attributed to the upward displacement of the center of the negative charge produced by the rising air current during the cloud development stage and the displacement of this center downward at the stage of maturity, when the rising current slackens and descending currents develop. The changes in the potential gradient above thunder clouds during active formation of canopies was observed by B. Vonegat et al. [166]. The actual process may be more complex (see Chapter II). /27

The average values of the potential gradient within the active portion of thunderclouds are equal to $(1 \text{ to } 2) \times 10^5 \text{ V/m}$. However, for the beginning of thundercloud development, the potential gradient must be $(1 \text{ to } 2) \times 10^6 \text{ V/m}$. Consequently, such gradients must develop in individual inhomogeneities even for a short space of time.

Significant inhomogeneities do exist in thunderstorm clouds. Judging by the change in the charge on an aircraft in inhomogeneities, concentration and size of cloud particles in them differ significantly from the average. The average size of the inhomogeneity zones in active thunderstorm clouds is equal to 200 - 400 m and extends to 400-600 m (Figure 1.8).

At average density values for the space charge in thunderclouds of $3 \text{ to } 30 \cdot 10^{-10} \text{ C/m}^3$, a significantly larger charge density may develop in inhomogeneities, above 10^{-8} and even 10^{-7} C/m^3 .

It should be pointed out that, regardless of the external similarity of the electrical structure of cumulus and thunderstorm clouds, the differences in the values of their charges and fields are so great that it is impossible

to view the former as a model of the latter or even as a stage of charge accumulation for thunderstorm processes. Since the time of transition from the Cu congestus stage to the Cb amounts to only a few minutes in all, only powerful electrification mechanisms that arise in the Cb stage can lead to the appearance of observable charges.

J. Latham and C. Stow performed rather complete investigations of the electrical properties of large convective clouds in 1965-1967 [124]: the intensity of the electrical field E , the hydrometeor charge Q , the water content of the cloud, the concentration and the nature of the distribution of small and large hydrometeors. They found that the highest values of E and Q occur in clouds in which there is an overwhelming number of particles with a complex structure, consisting of a chain of frozen supercooled droplets and ice crystals, and ice crystals in a large amount of supercooled water. In clouds which consist almost completely of pure water, E is small, while in ice clouds it is high.

Highly significant data were obtained on the electrical losses inside thunderstorm clouds and on the effective electrical conductivity inside them.

Back at the turn of the century, Wilson [169] noticed that the electrical field intensity, which changes sharply immediately after a lightning stroke, is restored relatively slowly to its initial value. The curve of restoration followed the exponential law, and the relaxation time constant was several seconds. Assuming that the reason for the increase in the electrical field intensity was the difference in rates of fall of differently charged particles forming the basic charge of the cloud, Wilson postulated a mechanism which would prevent linear growth of the field. He proposed that the increase in the electrical field intensity in the cloud reduces the difference in fall rates in differently charged particles. When the rates are equal, which occurs in a field with a voltage close to a breakdown voltage, approximately $3 \cdot 10^5$ V/m, the electrical field of the cloud ceases to grow.

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TABLE 1.8. ELECTRICAL CURRENTS ABOVE THUNDERSTORM CLOUDS

Area of investigation	Average current values, A	Maximum current values, A	Source
European territory of the USSR	0.1 - 0.2	1.4	[48]
Central USA	0.5	6.5	[107]
Florida (USA)	1.0	4.3	[152]

However, direct measurements in clouds, showing that the field does not exceed 10^5 V/m on the average, have forced a reexamination of Wilson's explanation. The assumption of high electrical conductivity of the air [97] in the vicinity of the measuring instrument on the ground, (which was used to explain the short relaxation time of the electrical field following a lightning stroke) turned out to be incorrect. The theory of Tamura [131] could not be used to explain the observed relaxation time, which views the restoration curves of the electrical field as a reflection of the transitory process of charge distribution in a thunderstorm cloud following lightning stroke to the equilibrium distribution which is dictated by the laws of a stationary field. It was necessary to support [27, 102, 103, 104, 132] the viewpoint that was expressed in 1956 [36] that the relaxation of the electrical field is connected to processes inside the cloud and to the existence of high, effective electrical conductivity in it. Electrical conductivity inside the cloud may be linked both to the ohmic conductivity and the conductivity produced by turbulence and convective movements. /28

Unfortunately, it has not been possible thus far to measure reliably the electrical conductivity inside clouds. The only results, which were obtained by Evans [101] with the aid of special sondes and which showed high values of ohmic electrical conductivity, cannot yet be considered sufficiently reliable,

since it is not clear how Evans excluded the influence of convection currents flowing over the measuring electrodes and the currents related to electrostatic charges on these electrodes.

Studies made in the free atmosphere of the time curve of changes in the potential gradient, following immediately after a lightning stroke, showed that the ohmic and turbulent electrical conductivities inside a cloud are very great [116, 53]. For the most probable relaxation time of the field, approximately 1-3 seconds, the total electrical conductivity in the cloud is about two orders of magnitude higher than the conductivity in a pure atmosphere approximately at the level of the storm cloud center. Hence, colossal electrical losses develop inside the clouds, which must be supplemented by the electrical machinery of the thunderstorm in order that lightning may develop in the cloud. /29

Methods of isolating those contributions which are made by the turbulent, convective and ohmic conductivities from the experimental data have not yet been devised, so that the method of determining the characteristics of cloud turbulence on the basis of observations of the restoration of the electrical field following a discharge is not yet clear. The development of appropriate methods will provide the investigator with a tool that will allow him to diagnose the internal state of clouds with the aid of apparatus located outside them.

It is clear that, if the electrical losses inside a cloud are not constant, they must be calculated in some way for predicting thunderstorms.

To evaluate the intensity of charging in clouds, as well as their role in the creation and maintenance of a charge on the ground, it is important to know the currents which are flowing outside the cloud, above and below it. Under average stationary conditions, when the cloud charges do not change significantly, the total currents flowing under the cloud (including the average

lightning current) are equal to the current above the cloud. A summary of data on the electrical currents above thunderstorm clouds, calculated on the basis of data from the measurements of the electrical field potential gradient above them and data on the electrical conductivity of the air, is shown in Table 1.8.

The electrical currents above thunderstorm clouds have been measured in only a few geographical regions. There is a general tendency for the current to increase above thunderstorm clouds toward the south. We have by no means enough data in order to extend them, as is often done, to more larger regions and to use them for judging the contribution made by thunderstorms to the total electrical field of the ground. Measurements of electrical currents above thunderstorms in various regions, and primarily in the tropics, may help to solve this problem, as well as to determine the contribution of the world-wide thunderstorm foci to the electrical field of the ground. This, in turn, could turn out to be very valuable in solving the problem of using data on atmospheric electricity as indicators of the tropical (and perhaps general) circulation of the atmosphere. We cannot afford going into detail on this problem within the framework of this booklet. Let us recall that modern estimates of the intensity of the charging processes of clouds [87, 88] and the role of thunderstorm clouds in the charging of the ground are based on the assumption that the current above an individual thunderstorm cloud and within it is equal to 0.5 - 1 A. The electrical conductivity current within the cloud being on the order of 0.1 A/km^2 , the charge generation rate must be $0.1\text{-}1 \text{ C/km}^2/\text{second}$.

Turning to the microstructure of a thunderstorm cloud, let us note that we have practically no experimental data on the charge of cloud particles in thunderstorm clouds. We have only the measurements of B. Phillips and B. Kintser (see Table 1.6), which indicate that the charges on cloud particles are high.

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According to the measurement results [42, 111, 156] we still are unable to put together a general picture of charge distribution on the precipitation particles in thunderstorms and rain clouds and directly above them. We know that there are extensive cloud zones where particles are charged similarly. The charges on the precipitation particles in thunderstorm and rain clouds are high and amount to $10^{-11} - 10^{-10}$ C. According to the data in [26] (thunderstorm clouds), they sometimes reach borderline values. Thus, J. Latham and S. Stow [124] found that the highest charges (up to $3 \cdot 10^{-10}$ C) are exhibited by complexly structured particles (see page 27)*. According to their measurements, both positively and negatively charged hydrometeors have been found at all levels within clouds, but the relative number of the former increase with an increase in air temperature.

If we can calculate the current density of the precipitation from results of direct measurements of the charge on cloud particles in thunderstorms [57, 70, 71, 72], it will be found to be great and to reach 0.1 A/km^2 . However, a slight current reaches the ground. According to a survey of data published by B. Mason [5], the current density for the majority of thunderstorms is nearly 10^{-3} A/km^2 , although it may reach 10^{-2} A/km^2 or even more for individual thunderstorms, i.e., the current from precipitation in clouds is much greater than the current which flows outside them. Obviously, this has something to do with the fact that a considerable portion of the current in the cloud precipitation goes to compensate for electrical losses in them.

In closing our survey of modern data on the electrical properties of clouds, let us note that recent studies have made it possible to obtain systematic data for several physical geographic areas on the macroelectric structure of clouds and the intensity of processes in clouds, and has revealed in certain areas of clouds a significant difference between electrical characteristics and in average values. The studies have also made it possible to gather information on microelectrical characteristics and electrical conductivity of the air in individual clouds in certain areas. It has become clear that clouds

*Translator's Note: This is found on page 30.

of similar types may differ significantly in their electrical properties under different physical geographic conditions. Even in a given region, the properties of individual clouds are very different, and it is necessary to study the statistical characteristics when they are combined, in order to make meaningful comparisons of the variability of the cloud properties in time and space. In particular, it is impossible to "stick together", as is necessary to do today, ideas regarding clouds on the basis of measurements of individual electrical characteristics in different clouds, developing under different physical and geographic conditions. Therefore, regardless of the successes which have been achieved, we must recognize the fact that the electricity of thunderstorm clouds, like the electricity of clouds of other types, has not been adequately studied. Extremely little has been done in the field of collecting combined material characterizing simultaneously both the macro- and the micro-physical electrical and nonelectrical characteristics of an individual clouds. However, it seems to us that it is only on the basis of such measurements that one can proceed from a descriptive to a physical picture of the development of clouds, during whose lifetime electrical characteristics may play an important role, as for example, Ns, Cu cong, and Cb. It is necessary to carry out complex studies of the electrical properties of clouds of characteristic physical geographic regions, in combination with studies of other physical cloud characteristics, in order to obtain a complete picture of their electrical state and the factors responsible for their development.

CHAPTER II

CAUSES LEADING TO THE ELECTRIFICATION OF CLOUDS

Let us determine how the electrical characteristics of clouds arise. /32
This is not a new problem, and beginning with M. V. Lomonosov, the author of the first theory explaining the development of cloud electricity, investigators have been trying to answer it. Laboratory and theoretical studies have made it possible to establish an array of water and ice electrification mechanisms and to suggest a host of theories and hypotheses explaining electrification of clouds based on these mechanisms. The majority of theories, hypotheses and schemes, although they are very interesting, appeared at a time when the electrical characteristics of clouds were not known, and consequent comparison with facts has revealed that they were not in a position to explain the phenomena that were observed in the atmosphere. The scope and intent of this book will not allow us to consider the history of the problem in detail. We will limit ourselves to modern theories and views, although they are becoming increasingly incapable of reflecting the true situation.

In the present paper, an attempt has been made to answer the questions of how cloud particles and precipitation particles become charged, how macro-electric characteristics of clouds develop, how these characteristics affect the development of clouds, and finally how probable it is that the electrical characteristics of clouds and their development are controlled by electrical factors.

The electrical structure of clouds develops as the result of interaction of two groups of processes. The first includes those which reinforce the

electrification of clouds. They include primarily those processes which lead to an accumulation of charges on the cloud and precipitation particles, as well as the processes that lead to the separation in the clouds of masses of particles charged with different electrical signs, or to the accumulation of charges of one sign or another in the cloud.

The second group includes those processes that prevent electrification of the clouds. Accumulation of charges on an individual particle is limited, since they are lost due to electrical conductivity of the air in the space surrounding the particle, as well as collisions with other particles that have the opposite sign on their charges or are relatively weakly charged. Accumulation of space charges in a cloud and growth of electrical fields in the entire volume are both counteracted by the conductivity currents that flow to the charged areas and currents formed by air movements, i.e., electrical currents of turbulent diffusion and convection. It is obvious that the more active the first group of processes, the greater the charges that will develop on the individual particles. The larger these particles, the greater the rate of separation in space of the differently charged particles and the greater the electrical fields that will develop in the clouds. The more acute the second group of processes, the smaller the electrical fields that will be generated by the clouds. Quasistationary conditions of the electrical state of the clouds are obviously achieved with equal rates of accumulation and the loss of charges formed by the two groups of processes. Predominance of the first group of processes over the second leads to an increase in the electrification of the cloud; dominance of the second over the first leads to a loss of electrification. It is obvious that the direction of natural electrification, as well as that which develops during active exposures, is determined by the ratio of the two groups of processes. /33

It must be pointed out that both groups of processes are closely related. However, for the sake of simplicity, we will view the processes of charge accumulation on the particles separately from the processes of accumulation in the clouds.

§ 1. Electrification of Particles in Clouds and Precipitation

With all of the diversity in the particle electrification mechanisms, they can be divided into two basic classes:

1. Electrification associated with the capture of air ions by particles.
2. Electrification associated with exchange of charges between particles (developing either following interruption of contact between them or after their disintegration).

Both kinds of electrification can take place in different ways in the presence and absence of an external electrical field.

Electrification associated with capture of air ions by particles. Let us consider the characteristics of the first type of electrification. This type of electrification can arise if the fluxes of positive or negative air ions onto the particle are not equal when they have a zero charge. The reason for the inequality may be, first of all, a different concentration and a different mobility of the positive and negative air ions, and secondly, a different ability of the particle of the given type to capture air ions of different polarities. In addition, electrification of a particle also takes place because the process of capture of the air ion itself by the particle has a random nature. The conditions of equilibrium arise at a specific distribution of charges on the particles. All of the electrification mechanisms that have been measured are combined under the common heading of the electrification diffusion process. This process of electrification has been studied in greatest detail theoretically, with a number of simplifying suggestions regarding the conditions at the particle-air interface and on the uniform distribution of the concentration of air ions in space near the particle (for example, [80, 86, 112]).

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A general form of the expression describing the distribution of particles having the capacitance C , on the basis of the number of elementary charges x on a particle, is given, for example, by Yu. S. Sedunov [80]:

$$v_x(x) = v_0 \left(\frac{e^2 P}{2\pi k T C} \right)^{\frac{1}{2}} \exp - \left\{ \frac{\left[x - \frac{k T C}{P e^2} \ln \frac{n_+ u_+}{n_- u_-} \right]^2}{\frac{2 k T C}{e^2 P}} \right\}, \quad (2.1)$$

where $v(x)$ is the number of particles having x elementary charges, v_0 is the total number of particles, e is the value of the elementary charge, P is the number of charges of the air ion, k is Boltzmann's constant, T is absolute temperature, n_+ , u_+ and n_- , u_- are the concentration and mobility of the positive and negative air ions, respectively.

Yu. S. Sedunov did not take the different "affinity" of the particles to air ions of different polarity into account, but it seems from general considerations that this is easy to do theoretically, by introducing under the sign of \ln a coefficient γ which indicates the relative capture ability of air ions of different polarities by particles of a given type.

The validity of Equation (2.1) was checked under laboratory conditions in a highly ionized volume of air that had been specially purified prior to the formation of fog, for example, by Gann [113]. He showed that charging of micron size particles follows the law (2.1). However, the numerous measurements of particle charges in stratus clouds and fogs that have been performed primarily by Soviet investigators (see Table 1.6) have shown that, even in those cases when a symmetrical charge is observed (n_+ , $u_+ \approx n_-$, u_-), the absolute average values (radius $r = 2-10$ microns) is approximately an order of magnitude larger than the ones predicted by theory, although the law of distribution $v(x)$ which is observed in practice is the same as that predicted by theory [80, 86, 112]. In other words, the dispersion σ of the observed distribution $v(x)$, $r = \text{const}$ is considerably larger than the theoretically predicted value σ^2 . In addition, the dependence of $|\bar{x}|$ on r as predicted

by theory has the form $|\bar{x}| = a\sqrt{r}$, while the observed relationship in the range $r = 2-10$ microns $|\bar{x}| = br$, where a and b are constant coefficients.

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In order to eliminate the difficulty of explaining the observed large $|\bar{x}|$ in fog particles, L. M. Levin [4], applying the theory of random wandering to the problem of the charge accumulation on these particles and suggesting the possibility of coagulation of similarly charged particles in the micron size range, pointed out a method of expanding the dispersion in the charge distribution on particles, and hence, a method of increasing the average absolute charge on the particles.

However, a great deal of time is required for establishing the stationary distribution of the charges, i.e., for obtaining the calculated values of σ . As a matter of fact, the delivery of ions into the atmosphere is limited (approximately ten pairs of ions are formed in the troposphere in 1 cc per second), while the consumption of ions for diffusion random charging is great due to the considerable probability of capture by the particles of both positive and negative ions. This was clearly demonstrated by L. S. Mordovina [70] who continued the calculations of L. M. Levin and performed new calculations for estimating the time required for establishing stationary charge distribution. She showed that the establishment of a stationary distribution of charges on particles at the values of σ observed in practice requires several hours, while in reality such a distribution is established relatively quickly.

Hence, there are no theories at the present time which explain the charging of particles in the "simplest" types of clouds (stratus) and in fogs. The known theories of charging of natural cloud and fog particles of micron size are insufficient.

The study of the reasons for electrification of fine particles of fogs and clouds is incomplete, and additional experimental and theoretical studies are necessary.

The existence of the selective ability of fog or cloud particles to capture air ions of different polarities which was proposed by Ya. I. Frenkel' [9] has not yet been experimentally confirmed. The ideas expressed along this line are preliminary in nature and require detailed experimental study. It would be interesting to perform direct or indirect measurement of electrical charges of individual condensation nuclei, on which particles of fog or clouds form. We are unable to dwell in greater detail on problems of diffusion charging of particles of micron size within the framework of this brochure, and refer the reader to the original works [4, 67, 68, 105].

Charges on cloud particles measuring 10-100 microns in radius have barely been measured. However, it is precisely in this size range that a transition takes place from comparatively small charges on small particles to rather large charges on precipitation particles. The values of the charges on the precipitation particles cannot be explained completely by the diffusion theory. /36

When the precipitation particles fall in an electrical field, conditions are formed for the charging of the particles, a mechanism which was proposed by Wilson [170] and worked out theoretically by Chalmers and Whipple [14] and by Drukarev [61]. The difference in the flows of air ions of different polarities on a drop develops due to the fact that the speeds of the drops and the flows of ions of one polarity, moving the field, are combined and, of another polarity, subtracted. The value of the equilibrium change in q_{∞} in this case is determined by the mobility of the ions of one or another, the rate of fall of the drop, and the magnitude of the potential gradient E of the electrical field of the atmosphere.

The charging of rain drops, when their rate of fall is great in comparison to the rate of ion movement and with equal polar electrical conductivities, is

$$q_{\infty} = 2.06 \pi \epsilon_0 E r^2, \quad (2.2)$$

where ϵ_0 is the dielectric constant of the medium and r is the radius of the raindrop.

This mechanism may be employed in a number of cases to explain the charging of precipitation droplets in strong fields under rain clouds, and also the overcharging of precipitation particles when they fall in an electrical field beneath the clouds, especially the above-mentioned lack of agreement between the calculated flow of precipitation in the clouds and that measured on the ground.

The impossibility of using the diffusion mechanism in its present form to explain charges of the observed magnitude on fog and cloud particles of micron size and the complete impossibility of explaining it by the development of large electrical charges on larger particles, including fog particles, has made it necessary to seek other mechanisms for the charging of hydrometeors.

Electrification of particles of clouds and precipitation, involving exchange of charges between particles. Numerous laboratory experiments have shown that disruption of the contact between particles of water and ice in any combination (water-ice, ice-ice, water-water) or destruction of the particles leads to the development of charges on the particles that participate in this event. The first studies in this area described it more phenomenologically than physically, the conditions under which electrification took place when droplets or snowflakes were destroyed (balloeffect), electrification when the droplets struck a cold, icy, rough surface, when they struck a cold surface, when the droplets struck a layer of rime, and the growth of rime (for example, [5]). Almost each one of these studies of the electrification process was accompanied by a theory of electrification for both the particles of the clouds and precipitation, as well as the clouds as a whole, based on a similar mechanism. The studies of electrical and microphysical characteristics of clouds made it possible to limit to some degree the universal application of these mechanisms. It became clear, for example, that the balloeffect of water droplets may only take place in very large drops of precipitation (mainly from cumulonimbus clouds). The impact of drops on a layer of rime is possible only in specific rare conditions when relatively

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large droplets develop in a cloud where the velocity of the vertical currents is small, etc. It was possible to compare the structure of electrical charges in clouds with a structure which would have developed under the influence of a certain mechanism, and the electrical efficiency of various electrification mechanisms was compared with actually observed rates of electrification (see, for example, [5, 46, 47, 50]). As a result, the number of mechanisms which could be responsible for the electrification of clouds decreased sharply from several dozen to less than ten.

An increasing amount of attention has begun to be focussed on the physical characteristics of the electrification process and its agreement with conditions that actually exist in clouds.

Theories of electrification must explain how charges Q are stored on precipitation particles which frequently are many times greater than the charges q created in individual acts of electrification. Data for Q and q taken from several authors are listed in Table 2.1. The charges on the precipitation particles were measured under natural conditions, while the q value was obtained under laboratory conditions. There is a considerable difference between the charges appearing on the particles at a single contact and the charges on the particles of precipitation. In the case of explosions of freezing particles, large charges (see below) may appear on the remnant of the particle, but they are less in magnitude than the charges on the precipitation particles in thunderstorms. Let us direct our attention to the considerable variation of the results of laboratory experiments as presented in Table 2.1, although an evaluation of the reasons for this lies outside the framework of this work.

It is particularly difficult to explain the electrification of the particles of warm clouds, since it was unclear until recently what the primary processes responsible for this were, besides capture of ions from the air (obviously insufficiently powerful). At the same time, however, the processes of electrification are sometimes quite intensive, so that in pure warm clouds thunderstorms may develop, although under admittedly very specific conditions that rarely develop.

The failure of agreement which we noted between the charges is reduced to a considerable degree (and even disappears) if we view the accumulation of charges on precipitation particles as an effect produced by the collective action of cloud particles on a precipitation particle.

TABLE 2.1. CHARGES ON PARTICLES OF PRECIPITATION (Q) AND CHARGES DEVELOPING ON PARTICLES (q) UNDER LABORATORY CONDITIONS (10^{-13} C)

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Source	Experimental conditions	q Absolute value for 1 particle	Q				
			Source	Sign of charge	Contin-uous rain	Shower	Thunder-storm
			On the ground				
	Artificial hail stone;		[5, 19, 84]	+	0.6-6	4-25	11-40
[142]	in a flow of super-cooled particles	1.5		-	1-9	9-20	18-60
[176]	in a flow of ice crystals 20-50 microns	$1.5 \cdot 10^{-5}$					
			In the cloud				
[176]	Formation of crystals with freezing of the surface in a stream of droplets:	$1.2 \cdot 10^{-2}$	[111]	+ and -			300-3000
[177]	with freezing of the surface	$7 \cdot 10^{-3}$	[42]	+ and -		100	
[154, 54, 128]	Explosion of freezing droplet; limiting values	20-270					
[154]	average absolute values	~ 10					

If we diverge from the phenomenological aspect of the problem, the electrification upon rupture of the contact between two particles is determined by the difference between their chemical potential and the charge that is separated on contact,

$$q = V_{1,2} C_{1,2} \left(1 - e^{-\frac{t}{\tau}} \right), \quad (2.3)$$

where $V_{1,2}$ is the contact potential difference for a given form of charge carrier, $C_{1,2}$ is the capacitance between the particles at the moment of rupture of the electrical contact between them, t is the contact time of the particles, and τ is the relaxation time determined by the dielectric constant ϵ_r and the electrical conductivity of the particles λ_r ,

$$\tau = \epsilon_r \lambda_r.$$

The value $V_{1,2}$ may be determined by the temperature gradient as is set forth in the theory of electrification of particles by Mason [5]. Mason feels that the concentration of protons H^+ in the cold parts of an icicle or hail stone becomes large, and the contact between the warm and cold parts leads to a positive charge on the latter. The value of $V_{1,2}$ may develop due to the contact of different phases, in which, for example, the mobility of ions OH^- of H^+ and the activation energy of the ions are different [158]. Due to the interaction of particles with different crystalline structures with different concentrations and mobility of dislocations and defects [159], owing to contact between materials of different chemical composition (which may take place in warm clouds), a combination of these factors may be effective (for example, the difference in phases and different chemical composition; the effect of E. Workman and S. Reynolds [172, 173], etc.).

Let us recall that Workman and Reynolds [172] and Ribeira [143] studied

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laboratory conditions in potential differences during the freezing process at the boundary of an ice-water interface containing weak solutions of electrolytes; the potential differences exceeded hundreds of volts. In clouds, in addition to the possibility, which they initially discussed [172], of separation of water from a cold hail stone, (which fell in the supercooled area of the cloud), the mechanism of separation of supercooled droplets during freezing of their surface also became possible. This mechanism was studied in laboratory experiments by L. G. Kachurin et al. [54, 21], B. Mason and J. Maybank [128], and also in detail by Hutchinson and Scott [154]. This mechanism turned out to be strong enough, even for those intensive electrification processes which take place in thunderstorms (see, for example, [21, 50]).

At first glance, it appears that the electrification of particles related with this mechanism does not take place in the way described by Equation (2.3). It is obvious that $V_{1,2}$ cannot exceed 1-2 volts, while in the Vorkman and Reynolds effect between ice and water potential differences developed which reached hundreds of volts. In reality, however, as shown in [43], during this effect a difference in potential $V_{1,2}$ is established at the water-ice interface, while the magnitude of the charges developed on both sides of the boundary is equal to q , the capacitance of the dual layer that forms at the first moment is great and amounts to approximately $C_1 = 10^7$ cm per 1 cm^2 surface for the interface. As a result of the continuous movement of the crystallization front, the charges that are formed separate from one another at the distance at which the capacitance falls to $C_2 = 10^3$ to 10^4 cm. If the charge q did not leak away, the difference that developed in potential between the two phases would be equal to $V_{lim} = V_{1,2} (C_1/C_2) = (10^3 - 10^4) V_{1,2}$. In reality, V is less than the indicated value of V_{lim} due to the leakage current.

In a quasistationary state of the process (with a constant velocity of the interface between the two phases), the leakage current compensates at a certain potential V for the current which tries to establish a contact difference in potentials $V_{1,2}$ on the moving interface.

We can assume that Equation (2.3) describes all the known cases of charge exchange between neutral particles.

A large particle which receives a charge q at the first collision will increase its charge collision with other particles similar to the first. If a precipitation particle with radius R collides with uniform cloud particles with a radius r , the limiting potential V_{lim} and the limiting charge Q_{lim} to which it may be charged are given by a relationship that is valid for $R \gg r$ [37, 38] /40

$$V_{lim} = A V_k \frac{R}{r}; \quad Q_{lim} = A q \frac{R^2}{r}, \quad (2.4)$$

where A is a coefficient on the order of several units (3 - 8). Hence, excessive collisions can lead (with any of the considered mechanisms for electrification upon rupture of contact) to a considerable increase in the initial charge. If we introduce the coefficient P , characterizing the charge ratio acquired by the precipitation particles following a number of contacts, to the one which it acquires upon breakage of the initial contact $P = Q/q$, the value of P can reach values of 10^5 to 10^6 and even more. In this case, the lack of agreement disappears between the magnitude of the charges measured on the droplets of precipitation and in the laboratory (Table 2.1).

Under real conditions, the precipitation particles may collide with cloud particles which have chemical potentials both higher and lower than those of the precipitation particles; the number of collisions may turn out to be insufficient for achieving the threshold charge. It is also necessary to keep in mind the portion of the charge on the precipitation particles may leak off due to the conductivity of the air λ .

In these cases, the change of the charge on the large particle with time t is given by the relationship [104]:

$$\frac{dQ}{dt} = Nq_{av} - NBQ - 4\pi\lambda Q, \quad (2.5)$$

where N is the number of collisions of a large particle with small ones, q_{av} is the average value of the transferred charge at one collision, determined by the spectrum of the properties of small particles, B is the amount of the charge which is transferred from the large particle to the small one due to the collector effect (for $R \gg r$, $B \ll 1$). If we assume that the colliding particles are spheres, we will have

$$Q_{av} = \frac{q_{av}}{\frac{r^2}{R^2} + 4\pi \frac{\lambda}{N}}, \quad (2.6)$$

and in this case, the value $P = Q_{av} / q_{av}$ can reach several orders of magnitude.

We could suggest, as proposed by L. Mordovina [70], that $q = \tilde{q}_1$ is a certain fluctuating value determined by several statistical properties of cloud particles. Then, if the dispersion of the charges \tilde{q}_1 acquired in individual collisions is given by the value σ_q^2 (assuming a Gaussian distribution of q), the distribution $W(Q)$ of the charges on the particles of precipitation will be given by the relationship /41

$$W(Q) = \frac{1}{\sqrt{2\pi}\sigma_Q} \exp\left[-\frac{(Q - Q_{av})^2}{2\sigma_Q^2}\right], \quad (2.7)$$

where $\sigma_Q = \sigma_q / 2B$ and $Q_{av} = q_{av} / B$.

From this relationship, we can draw several important conclusions. If, during the collisions of large and small particles, the former acquire charges of equal sign with equal probability (completely symmetrical distribution $q_{av} = 0$), then Q_{av} will equal 0 as well (Figure 2.1, a), but the actual charges on the particles and the clouds as well as the precipitation may be very significant. The difference between this mechanism and the one of random

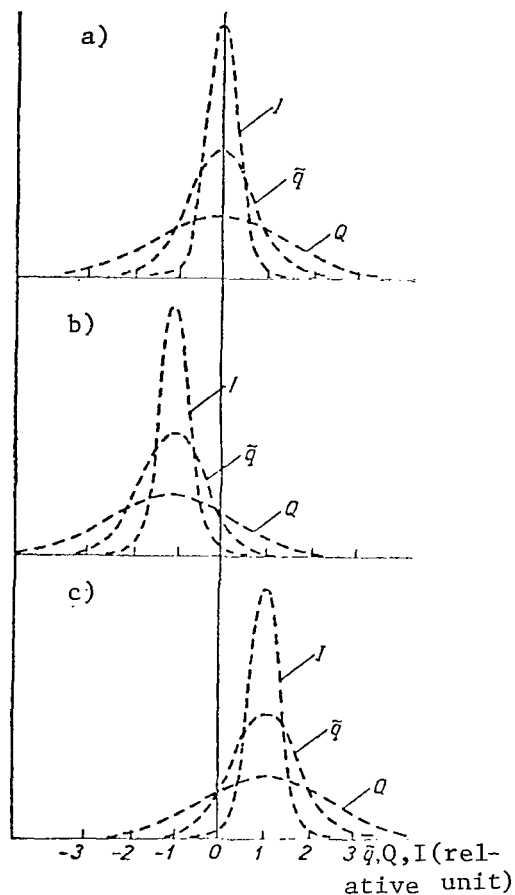


Figure 2.1. Diagram illustrating the change in the charge on particles with contact charging.

\bar{q} - charge transferred on contact;

\bar{Q} - equivalent charge;

\bar{J} - electrical current density of precipitation

charging that takes place during capture of ions by droplets consists in the fact that here each contact involves transmission of a charge of several tens or even hundreds of elementary charges. Therefore, the time required for developing large charges becomes comparable to that which is really observed in a cloud. This case, by the way, is apparently observed frequently in warm stratocumulus clouds, when the charges on precipitation particles reach (on the average) values of $3 \cdot 10^{-14} - 3 \cdot 10^{-15}$ C, but the current which is transmitted by them is close to 0, so that simultaneously the numbers of both positively and negatively charged droplets of precipitation will change. The average charge of cloud particles also appears to be equal to 0, since positively and negatively charged particles will be encountered with equal probability.

If the transmitted charge $q_{av} > 0$, then $Q_{av} > 0$ (Figure 2.1, b) and we will encounter in the precipitation both positively and negatively charged particles, but the number of the former (or in any case, their total charge) will be greater than the latter, and a positive precipitation current will flow from the cloud. The cloud

particles then assume on the average a negative charge, although both positively and negatively charged particles will be found. If $q_{av} < 0$, then $Q_{av} < 0$, and the precipitation is charged primarily negatively (Figure 2.1, c), while the cloud particles are charged positively.

This charging process may operate, obviously, in clouds with a solid phase, mixed structure and in purely warm clouds. Its realization depends on three principal factors: (a) differences in the physical and chemical characteristics of the cloud particles and especially the particles of clouds and precipitation; (b) the possibility of separation of colliding or rupturing particles in the electrical field of the cloud and (c) differences in temperature between the separating particles.

As we have already mentioned, lack of similarity between the physical and chemical properties of the separating particles may be linked both to a difference in their phase composition and chemical composition, as well as (in the case of crystalline clouds) a difference in the characteristics of the individual parts of the crystal surfaces. It is obvious that charging of macrospace in the cloud will be effective if there is some systematic difference in the dimensions (or parachuting characteristics) of particles of a single phase or a given chemical composition, etc.

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The effect of an electrical field on the electrification of particles may be noticeable either in areas where there is significant electrification, or in those cases when the increase in the field leads to an increase in electrification — a process involved in the avalanche growth of the field [44]. Finally, a certain contribution to the electrification of the particles and especially the spaces may be made by the temperature differential of the colliding particles.

It is necessary, however, to note that all of the factors which we have discussed may affect electrification at the same time and mask the effect of individual factors. Thus, when evaluating the effect of temperature, the action of the first two factors was found to be considerable, and it produced electri-

fication effects that exceeded the influence of temperature by several orders of magnitude. The difficulty in isolating these effects in pure form explains evidently the lack of coordination — and even contradiction in — the data obtained by different authors who studied the electrification of snow lakes and icicles, when the charges that develop on them under apparently uniform conditions differed in sign in various experiments and by factors of 10-100 in terms of magnitude. A change in the conditions causing an increase in electrification in some experiments leads to its reduction in others. The charges that develop in laboratory test particles are shown in Table 2.1. If there is any kind of systematic difference in the properties of the particles that fall with different speeds, the particles with a given rate of fall may be charged with one electrical sign, while those falling at another rate will be charged with the other. Thus, it may turn out that particles of clouds and fogs are charged differently. /43

In purely warm clouds, the value $V_{1,2}$ will depend on the difference in the chemical composition of the colliding particles and the difference in their temperature. In some cases, it is possible to have capture of surface-active substances (surfactants) by the drops, substances that were formerly nonexistent in nature, and may therefore lead to the development of high values of $V_{1,2}$.

It is unclear whether or not droplets could develop under natural conditions whose chemical composition differed for particles of different sizes, i.e., whether it was possible to have an event that would lead, as we have said, to separation of the charged macrovolumes. According to the data in the literature (for example, [10]), the concentration of impurities in small-drop and large-drop areas can differ on the average by as much as 10^2 - 10^3 , which would necessarily lead to $V_{1,2} \approx 100$ mV [38]. However, no one has yet attempted to find out how much difference there is between the chemical composition of small and large droplets in the same area of the cloud. Even less investigated is the situation of how much the chemical composition of the individual droplets differs. The difference between the temperatures of the colliding droplets may lead to $V_{1,2} \leq 1$ mV.

The conditions under which it is possible to have separation of the particles following contact in clouds with different phase composition are different.

In clouds, or their parts containing a solid phase, the particles separate after collision, in any case in the basic mass. In mixed clouds with thawing of hail, involving "explosions" of super cooled droplets, the separation of particles is certain but (as in pure droplet clouds) the fate of the colliding droplets in them has not been clarified. It is suggested that a portion of the droplets involved in such collisions may rebound [79, 82, 108, 114]. A. D. Solov'yev [82] produced criteria for estimating the probability of atomization of uncharged droplets during collision, merging, and reflection. However, no definite criteria have been obtained thus far which would make it possible to evaluate the role of the air layer between the colliding particles in terms of effectiveness of their merging, although its influence is great. The effectiveness of the drop merging is considerably affected by the electrical field which develops in the space between the drops. /44 As this field increases, there is a significant increase in the probability of coagulation [95, 117, 125]. The electrical field in the space may develop due to the charges of the drops themselves and due to the external field. Hence, as the charge on the drops increases and there is an increase in the space charges in the cloud, the probability of elastic collisions of the droplets will decrease, and this means that there will be a decrease in the effectiveness of the contact mechanisms of electrification. However, even if only 5 to 10% of the droplets undergo elastic collisions, the effectiveness of the contact mechanisms of electrification will be highly significant; thus, the values of P may reach up to $10^3 - 10^5$ [71]. It should be pointed out that the contact charging process may also take place in the absence of mechanical contact. The particles may exchange charges if the points of their surfaces are located at a distance of approximately $10^{-7} - 10^{-6}$ cm. As the charge on the particle grows, this distance will become larger.

The interaction of particles with different physical and chemical properties may, in the final analysis, as pointed out by V. Ya. Nikandrov [72],

occur even without contact, but in this case the rate of the process will be determined by the number of charge carriers in the air, i.e., by the air conductivity.

The number of charges that develop upon contact electrification may be considerably affected by an electrical field. The mechanism of this effect is shown in Figure 2.2. Drop 1 with radius R is falling in an electrical field with a potential E_a ; the density of the induced charge at some point i on the drop is equal to $\sigma_i = \frac{3}{4\pi} E_a \cos \alpha$. If a small drop (2 or 3) with radius r comes in contact with drop 1 or is at a distance from it at which charge exchange is possible, it will acquire a charge

$$q_u = Ar^2 E_a \cos \alpha, \quad (2.8)$$

where A is a certain coefficient which depends on the ratio of the drop radii, the time of their collision, and pressure.

The limiting charge which a large droplet may acquire due to this process, as in the case of the action of the Wilson mechanism, is

$$Q_{lim} = 12\pi\epsilon_0 E_a R^2. \quad (2.9)$$

If small drops (2) separate from the lower part of drop 1, they will /45 accumulate a charge on drop 1 whose field will increase the original one, which, in turn, will raise the intensity of this mechanism. The increase will last until the field is able to prevent a separation of small drops.

If the small drops (3) separate in the upper part of drop 1, the original field will decrease, and the mechanism will tend to weaken this effect.

In both cases, the intensity of the process increases with an increase in the number of elastic collisions with small droplets. Thus, depending on in what part of the large drop the elastic collision with the small droplets takes

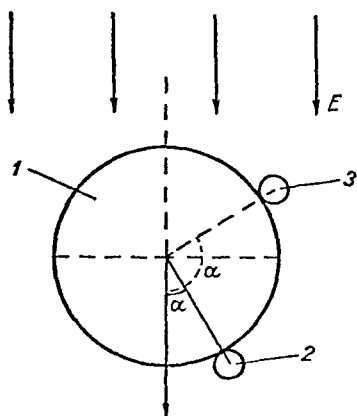


Figure 2.2. Diagram of electrification on contact in an electrical field.

place, this mechanism will lead either to an intensification or a deterioration of the electrification of the particles.

Elster and Geitel[100], suggesting that the elastic collisions take place in the lower part of the drop, felt this mechanism to be basic in the electrification of clouds. At the present time, this same mechanism is being studied by Sartor and his associates [146]. However, the lack of sufficient knowledge about collisions between small droplets and large ones does not allow us to determine reliably

at this time even the direction in which this mechanism operates: we do not know if it increases the electrification of the particles, or weakens it.

In comparison with the contact mechanism described above, the removal of induced charges is less pronounced in weak fields and cloud particles whose characteristics are not very uniform. If the charge of the particle according to (2.3) is represented by q_1 , and according to Formula (2.8) by q_2 we will have

$$\frac{q_1}{q_2} \approx \frac{V_{1,2}}{E_a \delta}, \quad (2.10)$$

where δ is the distance at which the large and small particles cease to exchange charges.

If the fields and the charges are not very high, $\delta < 10^{-6}$ cm and are in any case $< 10^{-5}$ cm. If $V_{1,2} = 10^{-3}$ V, i.e., $V_{1,2}$ is a very small value, then it is only in fields with an intensity ≥ 100 -1000 V/cm that q_1/q_2 becomes equal

to 1. Accordingly, the ratio of the limiting charges of the large droplets is $Q_1/Q_2 = V_{1,2}/rE_0$, i.e., with an increase in the size of the small particles, there is an increase in the role of the field in the cloud as far as the particle charging is concerned.

In strong fields and at high charges, where δ may reach values of several microns, contact charging associated with the action of the external field may become basic.

Hence, the contact mechanisms of particle electrification may manifest in all forms of clouds although their effectiveness differs under different conditions (Table 2.2). The strongest electrification of particles will take place in clouds with a mixed structure, producing intensive precipitation. Charging of particles in these clouds will decrease with a decrease in their density and thickness; in purely crystalline and purely warm clouds it will be weaker than in clouds with a mixed structure. The charges on the particles will increase with increasing inhomogeneity of the physical and chemical properties of the particles, and will increase with the density and thickness of the clouds. /46

TABLE 2.2. CONDITIONS FOR ELECTRIFICATION OF PARTICLES IN CLOUDS OF DIFFERENT TYPES

Type of cloud	Principal mechanism of electrification of cloud particles		Conditions for electrification of cloud particles and precipitation by contact mechanisms			Value of particle charges
	Capture of ions	Contact	Contact potential difference	Probability of elastic collisions	Mass of cloud particles having charges	
Stand Sc Ns	+	+	1 1 (T), 2-3 (c)	1 1 (r), 2 (c)	1 and 2 1 (T) 2 (c), 2-3 (c)	1 2
Cu and Cu cong	-	+	1 (T) 2-3 (c)	1 (r) and (c)	At low latitudes 1-2 (T), 2-3 (c)	1-2
Cb	-	+	3	3	2-3	3

Note: (+) The mechanism is readily apparent; (-) The mechanism is not readily apparent; 1 - low value; 2 - average value; 3 - large value; (T) warm clouds; (c) clouds with mixed structure.

§ 2. Accumulation of Space Charges in Clouds

The electrification of clouds as a whole (accumulation in them of considerable electrical space charges) requires, first of all, the development of electric charges on the cloud particles and precipitation, and secondly, the occurrence over a large area of a cloud of particles that carry primarily charges of one sign or another. For development of electrification, it is necessary that the processes of the first group, promoting electrification, dominate the processes of the second group, which suppress it. With equilibrium of the two groups of processes, a quasistationary electrical structure develops in the cloud.

The conditions for the particle charges accumulation were discussed in the preceding section, so that we will dwell only on the conditions for the development of unipolarly charged particles and volumes of air. If we ignore specific conditions, the space charges in all the clouds will arise under the influence of three factors:

1. Separation of differently charged particles in an external electrical field. /47
2. Separation of differently charged particles, exhibiting different aerodynamic resistances in a field of gravity. If the rate of fall of the equally charged particles differs considerably (for example, the rates of fall of particles of clouds and precipitation), the charge separation rate in the cloud may culminate in the appearance of an excess charge throughout the entire cloud following the fall of the precipitation and the development of an excess charge in the atmosphere, after the precipitation particles reach the surface of the ground.
3. The transfer to the cloud (or removal from it) of charged air with air flows due to convective movements.

The fourth possible method of charge accumulation in clouds (their transfer to the cloud due to turbulent diffusion in the atmosphere) is not realized, since the density gradient of the space charges at the cloud boundaries is such that it leads only to loss of charges from the clouds.

The processes which reduce the level of the space charges in a cloud are linked to four factors

1. The development of conductivity currents both inside and outside the cloud.
2. Turbulent diffusion, which weakens the rate of separation of the charges in the cloud itself and removes the charge beyond the limits of the cloud.
3. The effect of the force of gravity, under whose influence the space charges that accumulate on the particles may be carried beyond the limits of the cloud.
4. Convective movements that ventilate the cloud.

Let us see how the two groups of processes act in the electrification of individual types of clouds.

Formation of the electrical structure of stratus and stratocumulus clouds.

The electrification of these clouds would appear to be most naturally linked with the separation of charges in the electrical field of the atmosphere, developing in poorly ventilated cloud layers. With an ordinary positive direction of the field in the atmosphere, the upper part of the cloud must be charged positively and the lower part negatively. As a matter of fact, in order to achieve stationary conditions for the flow of vertical electric current in the atmosphere, it is necessary for the current density in the clouds to be equal to the current density outside them, i.e., to fulfill the following conditions:

$$E_u \lambda_u = E_0 \lambda_0 = E_l \lambda_l \quad (2.11)$$

where E_u and λ_u , E_0 and λ_0 , E_l and λ_l are the values of the potential gradient of the electrical field of the atmosphere and the conductivity at the upper limit of the cloud, in the cloud, and at its lower limit. The discontinuities in the field at the limits of the cloud are created by a space charge that concentrates at the boundaries. The electrical conductivity inside the cloud or fog is less than the electrical conductivity in pure atmosphere, since the particles of fog or precipitation actively capture ions from the air. This fact is supported experimentally by direct measurements in clouds and fogs [69, 32, 30].

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Due to the fact that the electrical conductivity of the atmosphere increases with altitude ($\lambda_u > \lambda_l$), E_u must be less than E_l , and the cloud as a whole must acquire a positive charge when the direction of the electrical field of the atmosphere is normal. In a similar manner, we can explain the unipolar charge of fogs.

More detailed information on the distribution of E in the cloud and near it may be gained if we use for our solution the ionization-recombination equation in its simplified form [69], using fixed values of λ_u , λ_l , and E_u , assuming a fixed microstructure for the cloud, and considering the possible development of convective currents inside and outside the cloud. However, the qualitative picture of the cloud charging need not be changed.

The system which is suggested and represents the cloud as a passive resistance connected in series with a resistance representing the atmosphere may explain the increase in the field in the clouds with an increase in their density, and unipolar charging of the cloud with a considerable difference in λ_u and λ_l . But this system cannot explain the effects observed in many instances. In many cases [3], the direction of the potential gradient within

the clouds does not coincide with the direction of the gradient in the atmosphere, and the polarity of the total cloud charge is opposite to that which was predicted. Moreover, the difference in the potentials at the upper and lower limits of the clouds frequently exceeds the drop in potential in the pure atmosphere. In these cases, it is necessary to assume that even slightly active clouds (in the electrical sense) — for example, stratiform clouds — do not produce precipitation and do not act merely as passive resistances but as electrical generators. The power of these generators compensates for losses which are created by the conductivity currents and the electric current of turbulent diffusion, whose density is about 10^{-2} A/m². The relative effectiveness of each generator in the cloud in specific cases may be established by measurements of the field intensity and the electrical conductivity in the clouds and in their vicinity. It is still not clear how these generators operate. The answer to this question is closely related to the development of studies on the charging of drops, conductivity, and fields in clouds.

Hence, even in apparently "simple" clouds, the processes that lead to their electrification have not yet been completely explained.

Formation of electrical structure of stratonimbus clouds. The characteristic outlines of the electrical structure of stratonimbus clouds may be explained in general outlines if we assume the diagram described in [3]. According to this system, charged precipitation falls from initially neutrally charged clouds. As the precipitation falls, a charge of the opposite sign accumulates in the clouds (if positively charged precipitation falls, a negative charge is accumulated, and vice versa). Under the influence of the field of this charge, in the upper part of the cloud and above it, and also beneath the cloud, charges of the opposite sign accumulate, forming the observed structure of the polarized cloud. The space charge of the precipitation superposes the space charge formed by the conductivity current below the cloud. The generator of the electricity in these areas of the cloud is, therefore, the charged precipitation particles falling under the influence of the force of gravity. The separation of the charges in the cloud prevents electrical conductivity and turbulent mixing. The electrical losses in the cloud are determined by the influence of these factors.

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These losses must also be made up by the electrical "generator" which achieves a stationary state in the cloud. For a model of a positively polarized cloud (Chapter I), the conductivity current density is assumed not to exceed 10^{-11} A/m²; the current density of diffusion is approximately equal to the same value. This means that the current density of the losses in the cloud will not exceed $2 \cdot 10^{-11}$ A/m². The power of the electrical generator operating in the cloud is very low and equals $4 \cdot 10^{-5}$ W/m², or 40W /km². It constitutes a small part of the power given off by the falling precipitation. We should keep in mind, however, that the figures given here apply to a typical cloud, and in individual clouds or parts of them both the current and power may exceed the indicated values by 1 or 2 and even 3 orders of magnitude. We can also expect that near the Equator, where the precipitation currents considerably exceed the values given in [151], electrical charges in the clouds are much greater than those given.

The system which we described above clarifies the relationship between the macrocharacteristics of stratocumulus clouds, and probably, the high stratus clouds that produce precipitation. It makes it possible to estimate the extent to which the changes in the current of precipitation, conductivity, and cloud turbulence might affect their structure, and the magnitude of the fields in them.

Changes by a factor of n in the magnitude of the precipitation current in the stationary state also change the magnitude of the accumulated charges in the cloud by a factor of n . A reduction of the effective conductivity by a factor of m will increase the accumulation of charges by a factor of m . With an increase in the water content and the number of drops, we can also expect an increase in the number of charged particles, and, as we noted earlier, a decrease in the conductivity, which promotes an increase in the charges and fields in denser clouds. The same effect (all other conditions being equal) may be expected with a decrease in cloud turbulence. At the indicated variations in precipitation current density and the effective conductivity, we can

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expect that in individual clouds or parts of them the charges and the fields will change by more than 10^3 times in comparison to the average values (Figure 1.1).

At the present time, on the basis of data on the spectrum of drops in clouds and their phase state, the thicknesses of clouds or their rates of development, it is impossible to calculate the currents of precipitation. For such a calculation, it would be necessary to calculate the charges of the drops and the solid particles. There is no effective theory which would make it possible to do this. General considerations that were given in the preceding section (see Table 2.2) clarify why the charges are greater in the thickest clouds than in thin ones, and the charges are greater in clouds with mixed structure than in warm clouds. A number of authors have studied the electrification of particles in stratonimbus clouds (for example, [14]), but the results of such investigations still do not allow us to progress further with these findings.

The solution of the complete problem of electrification of nimbostratus clouds (as, indeed, for clouds of other types) will require a detailed study of the microphysics of these clouds, both in nature and in the laboratory, as well as the development of a theory which will take into account the relationship between the macro- and the micro-processes. We shall return again to the problem of this relationship with a consideration of the electrical and other physical characteristics of clouds.

Formation of the electrical structure of cumulus and cumulus congestus clouds. According to the spectral composition of the particles, cumulus and cumulus congestus clouds do not differ very markedly from stratus and nimbostratus clouds; like the latter, convective clouds do not produce precipitation. Electrical characteristics of convective clouds, however, differ markedly from the characteristics of stratiform clouds, which do not produce precipitation. This difference is largely due to the fact that electrification of convective clouds, in contrast to the electrification of stratiform clouds, will not

have time to produce a quasistationary state. The formation of basic charges of convective clouds may be related to the effect of an external field, as was the case in stratus clouds, but the current $I = (E_a \lambda_a)_u$ will flow continuously into the cloud as it develops. Even if the top of the cloud ceases to rise, the intensive convection in it will carry away the stored charge, preventing its growth at the limits of the cloud [35]. Another reason for the accumulation of space charges in a cloud may be, according to the suggestion of Grene [109, 110] and discussed in our time by B. Vonnegat [26] and R. Storeb [153], a current of air rising from the ground, in which a convective cloud develops. The air at the surface of the ground, due to the electrode effect, usually contains a positive space charge. Rising with the jet of air, this charge enters the cloud, which captures it like a filter, storing the positive charge in this fashion. This charge creates a field which, due to the conductivity of the atmosphere, attracts charges of opposite sign to the external limits of the cloud. /51

Both of the effects considered may be explained more or less satisfactorily as the qualitative aspect of the initial formation of the basic charges of a conductive cloud. Rough estimates of the effectiveness of these mechanisms, with a consideration of the effect of ohmic and convective conductivity, do not contradict the values observed for the charges [35]. However, more detailed treatments describing electrical processes which lead to the occurrence of basic charges of convective clouds not producing precipitation do not exist.

The picture of the formation of large space charges of both signs, scattered over the entire volume of the cloud, is even less clear. We know these charges are formed in convective currents that penetrate the cloud. We can assume that an important role is played in the formation of the charges by the fact that the spectrum of the drops in the streams of convective clouds, in contrast to the spectrum in stratiform clouds, is not stationary for each given level, which leads to rapid transformation of the spectrum. However, even a qualitative system for the formation of macro- and microphysical charges

scattered in the cloud has not yet been worked out. It appears promising to use the possibility described above for electrification of the particles linked with their contacts and the difference in the physical and chemical properties of colliding particles. Thus, with a rapid rise of the stream, the particles at its limits, "trespassing" into the relatively fixed areas of the cloud, may have a chemical composition and temperature different from those which are inherently found in the old "inhabitants" of the level a factor, which must increase the electrification in the zones penetrated by the streams in the cloud. It may be that a contribution to the electrification may be provided by the effect discussed by V. Nikandrov [72], related to a different rate of evaporation of positive and negative ions by solutions.

What we said earlier about the necessity of experimental studies for establishing theories of electrification applies completely to the non-rain convective clouds.

Before moving on to an evaluation of the formation of cumulonimbus clouds, let us recall that the charges that accumulate at the stage of large convective clouds make up a negligible part of the charges that are stored at the stage of cumulonimbus clouds, and from this viewpoint Cu cong do not prepare the Cb stage. The opposite viewpoint, the one held by B. Vonnegut [26] who felt that the charge accumulated by the cloud as a filter in the Cu cong stage also creates the charges in the Cb, is proven by the measurements of charges in Cu cong [83, 35]. At the same time, however, we will see later on that the development of zones with considerable fields in Cu cong may play a role in the preparation of the particles for a transition to Cb. /52

Formation of the electrical structure of cumulonimbus clouds. By comparing the characteristics of cumulonimbus clouds with those of the clouds discussed earlier, we can discover the common features which the former share, both with nimbostratus clouds (presence of charged precipitation, coexistence of solid and liquid phases of water), as well as with cumulus congestus clouds (violent

convection, zones of considerable electrical and other microphysical inhomogeneities). In addition, at least the first and third of the three stages of development of the cloud occur in a nonstationary mode, while in the second (the stage of maturity) the stationary nature of the mode in thunderstorm clouds is continuously disrupted by lightning.

A characteristic feature of thunderstorm clouds is the presence of two basic electrical charges in the cloud: the relatively small, usually positive charge beneath it and small charges scattered throughout the cloud, which develop considerable local fields by virtue of their high concentration. This structure (see Figures 1.7 and 1.10) is made up from the structure of the cumulus congestus cloud in several (five or more) minutes. In other words, the process of development and separation of the charges in the cloud ("organized electrification") is unusually powerful, especially since the effective conductivity in clouds and consequently the loss of charges, is very high.

We can assume that the structure of cumulonimbus clouds that has been observed has to do to a large extent with the release of charged precipitation — the existence of large areas of unipolarly charged particles of precipitation in the cloud and observed directly beneath them in aircraft measurements [42] (we should recall that ground measurements of charges in precipitation cannot be detected due to overcharging of the drops in such areas). In this case, the principal charges of the clouds in the first stage may be produced due to the separation of differently charged large and small particles (Figure 2.3). If the positive particles move relative to the small ones through the active volume of the cloud, an electrical moment of the cloud M_0 will develop (if we disregard scattering of the field at the edges of a plane capacitor) shown in Figure 23 [116]:

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$$M_0 = j_3 h S \tau \left(1 - e^{-\frac{t}{\tau}} \right),$$

where j_3 is the current density of large particles, h is the thickness of the cloud in which charge separation takes place, S is the effective cross section

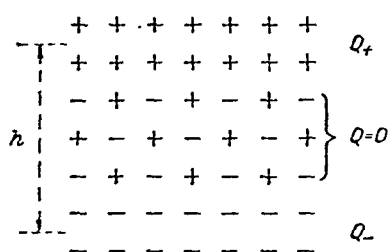


Figure 2.3. Formation of electrically polarized cloud.

Q_+ and Q_- = electrical charges accumulated in the upper and lower parts of the cloud.

of the separation area of the charges, τ is the relaxation time of the process in the cloud, determined by the effective conductivity λ_{eff} in the active zone: $\tau = \epsilon / \lambda_{\text{eff}}$, ϵ is the dielectric constant.

This equation correctly reflects the processes in the cloud when the parameters of the latter are not a function of time.

Obviously the processes of charge formation in shower and thunderstorm clouds have much in common, but for purely practical reasons more attention has been devoted to the formation of basic electrical charges in thunderstorms. They were discussed more or less in detail in [5, 14]. A common feature of the overwhelming majority of them is the fact that elementary electrification arises as the result of the action of contact phenomena, in which large particles are charged negatively and the small ones positively, but the details of the processes differ in different mechanisms. The separation of the particles of equal size takes place under the influence of gravitational forces.

Let us briefly describe the mechanisms which are apparently most active, and turn our attention to the considerable variability in the particle sizes and the altitudes at which thunderstorm clouds occur, as well as the definite localization of areas in which charges are produced with respect to the zero isotherm ($-5, -20^\circ \text{C}$). The ratios between the boundaries of this region and the heights of the bottom and top of the convective cloud have a critical effect on a thunderstorm activity, on the considerable role played by precipitation and the ice phase in the creation of conditions for the appearance of lightning, and on the fact that the negative charge on the cloud is not removed by precipitation. Therefore, Ye. Vorkman [27] proposed the following system

for formation of the basic cloud charges. Two processes may be active. They are formation of wet hailstones, and separation of water from them, and the collision of relatively dry and cold ice particles with drops of supercooled water, leading to partial freezing of the droplets, subsequent explosion and shattering of the water. The fine particles of water which explode and scatter are positively charged, as required by the mechanism of Workman and Reynolds. Both processes can take place in a zone where the precipitation particles grow due to the formation of a solid phase in them. In the zone where the growth of /54 the solid phase of the precipitation particles ceases and melting begins, collisions of precipitation particles with cloud particles leads to "spilling" of the negative charge, concentrated on the moist surface. Soon a large part of the charge transfers to the small droplets of water which are carried upward by rising currents. The rising droplets will interact with other ice particles, which have already acquired their charges due to the mechanisms described above. Hence, a cascade process operates, as the result of which a charge is built up in the negatively charged area by the falling icicles. The precipitation does not carry away a significant charge from the cloud. The lower positive charge of the cloud is formed as the result of intensive electrification of large droplets in powerful electrical fields (for example, [135]). More detailed information regarding this mechanism may be found in [27, 172, 173]. Latham and Stow, who measured the concentration and the charge of large and relatively small particles directly in various convective clouds, and also observed the shape of the ice particles, reached the conclusion that the electrification has to do primarily with the induction mechanism of J. Sartor [79] and the Raynolds-Brook mechanism [14, 142, 22] which operates during the collisions of ice crystals with graupel particles.

L. G. Kachurin [54] feels that the electrification which takes place during the explosions of droplets is sufficient for the principal charges of the thunderstorm cloud to be formed and maintained with the same losses that take place in the cloud.

We can assume [116] that, in general outlines, the formation of the principal charges in cumulonimbus clouds, regardless of what the mechanism of charging the individual particles may be, is similar to the charging of nimbostratus clouds, but with the difference that stationary conditions are not achieved in cumulonimbus clouds. However, on the whole, it is charged negatively, due to the positively charged precipitation, while in its upper part (due to the conductivity currents) a positive charge is stored.

This charging system is shown in Figure 2.4.

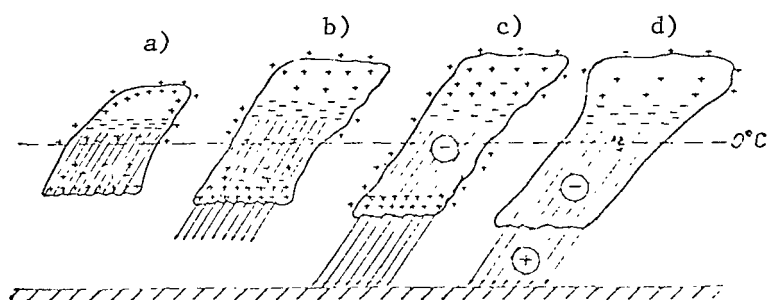


Figure 2.4. Charging of cumulonimbus cloud (according to I. Imyanitov).

a, b, c, d = successive stages of precipitation.

All of the charging mechanisms which we have discussed, including the method for explaining the field sign reversal above cumulonimbus clouds in the course of their development (transfer of negatively charged precipitation particles by a powerful convective current to the upper part of the cloud during the first stage of its development [52], or the fall of positively charged precipitation at this stage), are hypothetical to some degree, since we lack sufficient data on the microphysics and electrical characteristics within clouds. In addition, the development of ideas regarding the electrification of thunderstorm clouds is valuable not only from the cognitive standpoint,

but primarily for the development of methods for influencing thunderstorms.

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Measurement of electrical characteristics within clouds in conjunction with the measurements of aerological and microphysical characteristics has been and still is one of the most important problems in the investigation of cloud electricity [13].

The accumulation of space charges in a cloud is hindered by losses. Until recently, it was felt that the electrical currents that flow above thunderstorm clouds are approximately equal to the currents in the clouds. In 1956, another viewpoint was expressed, and in 1965, E. J. Workman [27] stated that a thunderstorm cloud must be considered to be an electrical machine with very poor insulation. It is natural that electrical charges may be lost due to the electrical conductivity of the medium. Direct measurements of electrical conductivity in thunderstorm clouds could not be performed until recently, but measurement of the field relaxation time following a stroke of lightning showed that the effective electrical conductivity in the active part of the thunderstorm cloud is several tens of times higher than that in the surrounding atmosphere, and can change from one cloud to another. Consequently, the change in the magnitude of the charge on cumulonimbus clouds may also change noticeably for the same reason. The reason for such great electrical conductivity is not clear, but may have something to do with increased ionization in the active part of the cloud, and therefore is reduced to ohmic conductivity. Incidentally, in cumulonimbus clouds, in contrast to Ns, an increase in the number of particles may lead to an increase in electrical conductivity. Increased effective electrical conductivity may be a consequence of high turbulence and divergence of vertical airflows, and consequently may have a nonelectrical origin. However, regardless of what the specific mechanism may have been for formation of conductivity in the cloud, it is clear that its changes can control the probability of the thunderstorm process in the cloud. In a cloud with a relatively weak electrical precipitation current, thunderstorm phenomena may arise if the conductivity /56 is low. On the other hand, thunderstorm phenomena may not develop if the conductivity is high in a cloud with strong electrical precipitation currents [116].

Failure to predict thunderstorms in a number of cases may have to do with failure to consider the influence of cloud conductivity. Difficulties in predicting nighttime thunderstorms, characteristics of the development of thunderstorms above water, latitudinal characteristics of thunderstorm development, etc., may be largely related to the magnitude of the electrical losses in the clouds and their electrical conductivity. We know for example (Table 2.3) that, as we move toward the equator, the minimum thickness of the clouds which can produce thunderstorm phenomena increases [116]. It would appear that, as we move toward the equator, the possibility of thunderstorms becomes greater due to the greater influx of heat and moisture. While in the north thunderstorm phenomena will develop in a cloud with a given thickness, they will appear with more likelihood when this cloud moves toward the equator. In reality, (Table 2.3), the opposite effect is observed. As a cloud moves toward lower latitudes, thunderstorm phenomena arise in it only if the clouds are thick, and greater currents flow in them and higher charges develop than at higher latitudes. The increase in the maximum thickness of clouds which produce lightning, as one moves toward the equator, usually has to do with an accompanying increase in the level of the zero isotherm, since it is felt that, for accumulation of charges, development of an ice phase is necessary. The data in Table 2.3, however, indicate that, as the latitude decreases, the thickness of the supercooled part of the cloud increases. In other words, merely an increase in the zero isotherm would be insufficient to explain the growth that is noted in the minimum thicknesses of thunderstorm clouds.

We can assume that there is an increase in turbulence and convection in clouds which move toward lower latitudes, i.e., there is an increase in the effect of conductivity. Then the accumulation of electrical charges in the clouds becomes more difficult. The cloud must contain more drops, and the drops themselves must reach larger sizes and accumulate larger charges in order to create sufficiently large space charges. But this requires high velocity of vertical currents in the cloud, and correspondingly greater thicknesses.

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TABLE 2.3

Area studied	Minimum thickness of clouds forming thunderstorm phenomena with 90% probability, m	Average altitude of isotherm 0° C, m	Average thickness of layer of supercooled water, m	Source
Leningrad	5100	3000	4200	[116]
Cape Mirotomissaki (Japan)	7500	4900	5000	[178]
Florida (USA)	7900	4400	5500	[179]
New Delhi (India)	9400	5600	6000	[180]
Poona (India)				[181]

The convection dependence of the criterion for the danger of thunderstorms Y , one of whose components is the altitude of the upper limit of the cloud, was noted by Ye. M. Sal'man, S. B. Gashina and L. I. Kuznetsova [78]. According to their data, there is a linear relationship between Y and the instability energy E characterizing convection. This relationship has the form $Y = aE + b$.

If the electrical losses in the clouds decrease significantly — i.e., if there is a decrease in conductivity — thunderstorm phenomena may arise, even in systems with very small electrical currents in which attenuated electrification processes are taking place.

Thus, for example, we can explain the appearance of lightning in warm clouds [93, 130]. As a rule, thunderstorms of this kind are observed near water during the evening hours, i.e., when we can expect reduced turbulence.

A very valuable means of studying the losses in clouds is the measurement of the field relaxation time following lightning. We can expect differences in the relaxation time of the field of thunderstorms which arise in clouds of mixed structure and in warm clouds.

The reasons for the formation of particle charges have been discussed in Section 1 in general form. A more concrete analysis is precluded by the following: Firstly, as we have already pointed out that our knowledge of the microphysics of processes in thunderstorm clouds is absolutely insufficient. Consequently, it is impossible to test the agreement of specific theoretical systems with the actual state of the clouds. Secondly, as we shall demonstrate later on, electrification processes in thunderstorm clouds, which are determined by their microphysics, may themselves have an important influence on the microphysical state, and consequently, may control macroprocesses in the clouds.

Let us merely note that the mechanism of contact successive electrification [38, 71] is sufficiently effective, so that it can explain space charges both in mixed and even in warm cumulonimbus clouds.

A specific characteristic of cumulonimbus clouds is the presence of large space charges in the zones of inhomogeneity which are scattered through the entire volume of the cloud. The appearance of these zones, as in the case of cumulus congestus clouds, is again related to the presence of rising and descending movements, although in this case, it is not clear why large space charges develop in the flow zones. We can only assume that the distribution of particles and charges at a given level a cloud without flows rapidly takes on a quasistationary nature, in which the development of the cloud — a change in the spectra of the particle dimensions and charges — stops, i.e., the entropy of the system increases intensively. The appearance of flows in the cloud — which transport charged particles (with spectra of particle dimensions and charges established for a given level) to some other level, for which these spectra are not stationary, with spectra transformation which

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accompanies this process — leads to a decrease in the entropy of the system and acceleration of the cloud development.

Let us discuss the role of inhomogeneities in the formation of lightning in the cloud. The field intensity which is produced by the basic charges in the cloud is too small to generate thunderstorm discharges. In inhomogeneities, a field intensity could develop (although briefly) sufficient to start the discharge, whose development is maintained by the basic charges stored by the cloud. In clouds, the probability of inhomogeneities increases with an increase in the intensity of convection and with the growth of turbulence. Hence, on the one hand, the turbulent streams in the cloud prevent the development of thunderstorm phenomena, since they promote dissipation of the basic charges of the thunderstorm cloud. On the other hand, they promote the development of lightning, which contributes to the formation of electrical inhomogeneities in the cloud. Another factor may be related to this dual role of convection and turbulence in the cloud which complicates the prediction of thunderstorm phenomena, especially in "atypical" conditions (thunderstorms over water, nighttime thunderstorms, winter thunderstorms).

We should note that in many cases high electrical basic charges can exist in clouds which are sufficient to maintain thunderstorm discharges; at the same time, the inhomogeneities that are necessary for its initiation may be absent. In those clouds which develop at middle latitudes in winter, early spring and late fall, there is usually no turbulence in the region of large-droplet precipitation; the thickness of these clouds may be 1-2 kilometers at most. The entry into such clouds of an electrically charged aircraft which can play the role of an electrical inhomogeneity (it can begin an electrical discharge) leads to the development of lightning, which strikes the aircraft [2].

In thunderstorm clouds, a correlation between nonelectrical and electrical processes is most clearly evident; for example, the intensity of precipitation and convection with electrification of clouds. The disclosure of these

relationships and their nature is of considerable importance for methods of diagnosis and physics of clouds. It has already been noted that such a characteristic of cloud processes as the intensity of the electrical field in its vicinity is an indicator of the development of the cloud in the natural state and of a cloud which is subjected to active influences [39, 83, 116]. The influence of turbulence on the development of lightning, etc., has also been discussed.

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Unfortunately, we still do not have a complete qualitative picture of the relationship between the nonelectrical and electrical processes in cumulonimbus clouds, not to mention the quantitative aspect of the phenomena. The possibility of disclosing the causative relationship of electrical and nonelectrical processes in clouds is based on answers to questions of how meteorological processes in clouds affect electrical ones, and how the latter affect nonelectrical processes and phenomena. Current information which makes it possible to answer the first question has been given above. Let us try to answer the second question, taking into account the fact that this answer may also be extended to processes which take place in other than cumulonimbus clouds.

§ 3. Influence of the Electrical Characteristics of a Cloud on its Development

The most disruptive intensive showers and the cloud which disappears without a trace in good weather owe their existence and their entire history to the formation of individual particles of precipitation and the effectiveness of their interaction. The collective nature of the effects in the cloud unquestionably complicates a consideration of the changes in individual particles. We have already pointed out that the increase in the charges on particles is accompanied by a growth in the field of the cloud, expressed in the increase of charges. Subsequent collisions of particles lead to accumulation of charges on them. L. Levin and Yu. Sedunov [65] state: "... In recent years, there has been a gap in the study of microphysical phenomena in clouds. The emphasis has shifted from a study of elementary processes to a study of the behavior

of an aggregate of droplets ..., and a need has arisen to reduce the problems of formation of precipitation to a mathematical model of the phenomena and a solution of the appropriate system of equations." Despite the accuracy of this statement of the problem, we must note with regret that it cannot be solved in a form which is suitable for practical use if we do not know the constants of the kinetics of the development and growth of cloud particles and the constants of the paired interactions between them. Hence, the problem of the collective processes in clouds merely extends, but does not replace, the problem of elementary processes.

Under laboratory conditions, a great many processes have been studied in which electrical forces influence the development of particles. The charges on drops with a radius of less than 10^{-6} cm influence the conditions of condensation of vapor on them [8]. In strong electrical fields, drops may be elongated and broken up [121, 122]. Under the influence of electrical forces, /60 the conditions of collision and fusion of particles of clouds and precipitation change. Under the influence of electrical forces on particles, there is increased growth of hoar, and the electrical forces affect the probability of freezing of the drops to some degree [139, 106, 129]. The role of macroeffects may be great. It has been shown in qualitative estimates that electrical forces may influence the time the drops remain in the cloud, and thereby may promote its growth. The particles which are charged near the lightning channel and scattered throughout the cloud may lead to a very rapid growth of the drops in the cloud [121]. Finally, it is possible to have a complex interaction of electrical and nonelectrical processes with the presence of feedback between them. Thus, the electrical fields in the cloud depend on the number and charges of the particles, and the particles which are destroyed in the electrical field are electrified: the coefficient of coagulation of the particles that are formed is affected by their charge. The explosion of a freezing drop is accompanied by electrification of the fragments that fly out in all directions. At the same time, these fragments, striking supercooled droplets, trigger a series of new explosions, etc., which leads to the formation of a field in the cloud

which affects the probability of freezing. To solve the problems concerning the influence of electrical characteristics on the "nonelectrical" processes in clouds, it is necessary, first of all, to select — from the entire collection of electrical effects — that effect which can take place in clouds of all types. Secondly, it is necessary to determine the constants of the kinetics of the development and interaction of cloud particles, and their values must be compared with the constants which act in the absence of electrical forces. Finally, in the third place, we must determine the rates at which the process takes place in the clouds. To solve the first problem, an important role is played by the comparison of experimental data on cloud electricity with the data from laboratory and theoretical studies of the influence of electrical forces on the conditions of particle development, including their paired interactions.

Let us discuss the influence of electrical forces on the behavior of particles in clouds. In many cases we cannot explain the phenomena which are observed without introducing any additional factors. Let us recall, for example, that convective clouds develop so rapidly that only coagulation of the cloud droplets can insure the required rate of growth of the droplets; at the same time, however, (according to Hocking [115]), drops with a radius less than 19 microns cannot collide (according to Davis and Sartor [98], the coefficient of their coagulations [Figure 2.5] is very small), while the condensation growth of droplets to a radius which exceeds the radius of the forbidden coagulation requires a much greater time than the time necessary for cloud development. Without dwelling on the various assumptions to explain this contradiction, we will only note that the appearance of charges on droplets and electrical /61 fields is able to remove this contradiction, if the forbidden coagulation area is shifted toward small droplets. Moore and Vonnegut [134] observed an intensive fall of precipitation from highly electrified clouds a very short time after the development of a radar echo from the cloud. They estimated that the effectiveness of the capture of the droplets in these clouds was 4-10 times greater than the values assumed for nonelectrified clouds. The effectiveness

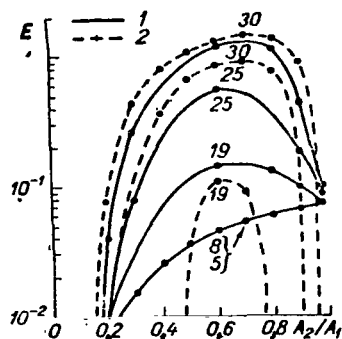


Figure 2.5. Coefficient of collision E of two uncharged drops in the absence of an electrical field, according to [135].

A_1 - radius of large drop;

A_2 - radius of smaller drop;

1 - according to [135];

2 - according to [134].

Numbers above curves:

A_1 values, in microns.

of the capture might have changed due to the increase of the relative capture cross section (collision coefficient) and an increase in the effectiveness of merging during collisions.

Influence of electrical forces on the probability of particle collisions. Calculations of the influence of electrical forces on the collision coefficient of droplets were performed by Levin [4, 64], Levin and Sedunov [66], Krasnogorskaya [59, 60], Semonin [148], Davis and Sartor [98], Sartor and Miller [146], and others. From their calculations, in particular, it follows that the electrical forces have little if any influence on the collision coefficient of drops with a diameter greater than 50 microns. The collision coefficient of droplets with a diameter less than 10 microns (with the appearance of electrical charges which are found in all forms of clouds) is much greater than zero. The influence of

electrical forces on the collision of larger cloud particles is connected with the appearance of electrical fields with an intensity greater than 10^4 V/m, and/or charges on particles with more than 1000 elementary charges. The effect of electrical charges may be increased if we consider the effect of turbulent-electrical coagulation [66]. This mechanism becomes effective when the charges on the drops exceed the observed average values 3 to 10 times.

It follows from the calculations of N. V. Krasnogorskaya [59, 60], for example, that if the collision coefficient of two uncharged particles with radii of 15 and 20 microns equals 0.8 in the absence of a field, then in vertical fields with intensities of 2×10^5 , 6×10^5 and 10^6 V/m, the coefficients of capture will be equal to 1.6, 5.2 and 8.4, respectively. For uncharged

droplets with radii of 6 and 8 microns, the capture coefficient is equal to zero in the absence of a field, and 1 and 4 in fields with intensities of 5×10^4 and 10^5 V/m, respectively. The appearance of charges of corresponding signs on the droplets may further increase the capture coefficient.

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We have already mentioned earlier that in clouds of different forms zones with different degrees of probability may develop in which an electrical field exceeds the average many times.

If such a probability is low in the case of St and Sc clouds, then in the case of Ns at middle latitudes a field with an intensity of more than 10,000 V/m is found in 0.1% of the total volume, while in cumulus congestus clouds and cumulonimbus clouds the probability of encountering a field with an intensity of more than 10,000 V/m is greater.

In these zones of increased fields and large space charges, drops will most likely be found whose charges are many times greater than the average charges of droplets. The fields and charges that develop in these zones are sufficient to significantly increase the collision coefficient of the cloud particles (Figure 2.6). It is striking to note that the more intensive the precipitation that falls from the cloud, the faster the development of the cloud takes place and the more likely it is that we will find in it electrically /63 active zones, in which the electrical characteristics may intensify coagulation significantly. If in Figure 1 the correlation of the average intensity of the electrical field with the radar echo of the clouds has no physical basis, the question then arises: is it possible that the development of the cloud involves not only the average fields whose magnitude usually is small, but also the fields which differ sharply from the average, which are usually encountered more frequently, the larger are the average fields? Let us recall that out of 10^6 to 10^7 cloud droplets, only one becomes rain. How does this happen? One alternative is possible: either the raindrops develop as very small probable colossal fluctuations produced by average conditions that exist in the cloud and are generated with equal probability at any point in the cloud

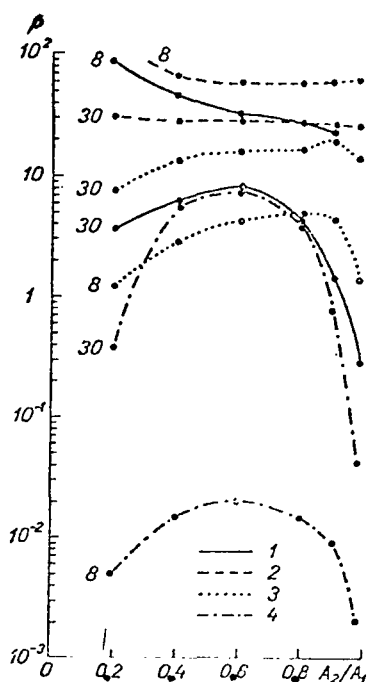


Figure 2.6. Intensity of collisions $P = E (U_1 - U_2)$ in cm/sec, equal to the product of the coefficient of collision by the difference in the fall rates of the particles, as a function of the charge on particles and the intensity of the electrical field, according to [135].

- 1 - $E = 0$, $Q_1 = Q_2 = 8 \cdot 10^{16}$ C;
- 2 - $E = 3.3 \cdot 10^5$ V/m, $Q_1 = -Q_2 = 8 \cdot 10^{16}$ C;
- 3 - $E = 3.3 \cdot 10^5$ V/m, $Q_1 = Q_2 = 0$;
- 4 - $E = Q_1 = Q_2 = 0$.

at a given level, or these drops develop in cloud zones whose conditions differ greatly from average conditions — in unusual nurseries of raindrops, manifested as a particular small fluctuation against a background that considerably exceeds the average. If the second system is valid, then rapid development of convective clouds and the relationship of the cloud precipitation intensity to the electrical characteristics of the clouds becomes clear.

As strange as it seems, current knowledge of cloud physics does not lead to a solution of the alternative. Current knowledge of the processes in clouds is based on average cloud characteristics. It may be that the difficulties encountered by the theory of precipitation may be linked to this situation to a large extent; on the basis of average values, this theory must explain the fluctuations which differ many times from the average. But is it possible to calculate the probability of the occurrence of a genius by investigating the mental capacities, let us say, of a thousand people who show up for examination? In fact, all of the information that we have about the characteristics of

the spectra of droplets in clouds all over the world was obtained from an analysis of $1-10 \text{ m}^3$ of cloud air. Therefore, there is no possibility of explaining the characteristics of a spectrum in particular zones of clouds. Even when such a possibility has occurred, investigators have overlooked it. The authors of [119] studied the distribution of water content in clouds, and, although the water content spectrum has a definite tendency to cover the region of higher values, the author [119] approximates it by a Gaussian distribution.

At the same time, however, the increase in the probability of occurrence of precipitation or the appearance of relatively large particles in a small volume of cloud has been tested quite reliably. Let us recall that, during active influences on the cloud, the reagent initially falls only into a small part of the cloud, amounting to $10^{-15} - 10^{-16}$ of its volume [5a]. Therefore, the version of growth of cloud droplets from which the raindrops later grow is very probable in zones of the cloud with special conditions.

Obviously, it is necessary to have further experimental studies of the small-scale inhomogeneities of the space charge and the measurements of the spectrum of dimensions and charges of individual drops in such inhomogeneities. It is also necessary to study the effect of small zones of preferred coagulation on the development of the cloud as a whole, so as to reach a solution of the problem regarding the possible influence of electrical forces on the non-electrical processes in clouds. It should be pointed out that a study of the reasons for the development of such electrical inhomogeneities, even when they have nothing to do with the development of clouds, is important for an understanding of the processes of cloud electrification.

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All of the general considerations expressed regarding the possible action of electrical characteristics are based on information about theoretically determined collision coefficients of two charged particles, falling into an electrical field and without it. However, such calculations are performed for an idealized case of two solid spheres. In addition, as we can see from [36], the calculations may be subject to errors due to the calculation itself.

Therefore, it is extremely interesting to check experimentally the results of the theoretical calculations. The natural conditions must be modelled sufficiently well. Thus far, experiments studying the interaction of charged particles in electrical fields and without them, modelling natural conditions sufficiently well, have not been performed. This is a problem for the future.

Effect of electrical forces on the probable merging of colliding particles. Collision of particles in clouds does not necessarily lead to their merging. If n particles out of n_0 particles that collide with a particle-target merge with it, the merging effectiveness coefficient $k^2 = n/n_0$, the coagulation coefficient of particles is $k^* k_1 k_2$ where k_1 is a coefficient which characterizes the probability of collision.

Aganin [17], on the basis of experiments of Rayleigh, noted that not every collision between droplets or against a flat surface leads to merging. He did show, however, that under the influence of electrical forces the probability of merging increases. Aganin proposed that, in a strong field which develops when droplets come close together, a small tongue which joins the drops comes out of one of them and (depending on the relative rates of fall of the drops, the sizes and charges, as well as the intensity of the external field) the neck which is formed either leads to a merger or breaks off. Later on, this assumption was confirmed by calculations and experiments (see surveys [82, 121, 123, 131]). It was demonstrated in [121, 123] that a protuberance develops on one of the merging charged particles (or drops merging in the field), directed toward the approaching drop. It is mentioned in the survey [123] that the /65 instability which develops under these conditions is usually accompanied by ejection of a thin stream of water, corresponding to the theory of Aganin, which is directed along the lines of the field and strikes the adjacent drop. If, as was suggested by many authors [82, 117, 125], a thin film of air prevents the merging of the drops, the stream which is ejected into the field may overcome the effect of this film. As a matter of fact, as was shown by Allan and

*Translator's Note: Missing symbol in original text.

Mason [91], and later by others [82], the average duration of drops that collide in an insulating liquid decreases considerably if the droplets are charged or are in an electrical field. They have attributed this effect to a thinning of the film which divides the liquids through the action of electrical forces; it is more likely that this effect can be explained by the unifying action of the stream ejected by the field.

Ideas regarding the influence of electrical forces on the effectiveness of merging were supported experimentally by many authors. Telford and Thorn-dyke [161] observed that the effectiveness of merging of colliding, noncharged particles with a radius of 30 - 35 microns was equal to zero in the absence of an external field and gradually increased with an increase in the intensity of an applied vertical field, beginning with 10^5 to 3×10^5 V/m. Woods [171] showed that the merging effectiveness of equally charged droplets of similar sizes (radius less than 40 microns) increased linearly with an increase in the charge above the threshold value of 1.5×10^{14} C. If the drops were charged with the same sign, they would not merge. Goyer et al. [108], investigating collisions of droplets with radii of 100 and 600 microns in an electrical field, found that the merger coefficient changed from 0.3 to 0.9 with a change in the intensity of the external field from 0 to 3000 V/m. Unfortunately, the results which were obtained by these authors, like those of a number of others, were obtained under conditions that could not be compared and were qualitatively inaccurate when applied to conditions that exist in clouds. But the qualitative picture indicates that in zones of cloud electrical inhomogeneities there must be a considerable increase in the merger of colliding droplets, and the coagulation coefficient will increase.

In strong electrical fields, there is an increase in the effectiveness of solid particle combinations as well. According to the data of Latham and Saunders [123, 147], the coagulation coefficient of ice crystals with an ice sphere increased rapidly with an increase in the intensity of the electrical field above the threshold value of 5×10^4 V/m. According to the data in [123],

an increase in the field intensity from 10^5 to 3×10^5 V/m led to an increase in the mass of the ice sphere colliding with the ice crystals, changing from 10 to 100%. It should be noted that the capture of crystals took place in a temperature range up to -50° C, while in the absence of a field at temperatures below -25° C capture of crystals became negligibly small. Let us recall that in all forms of supercooled clouds which produce precipitation it is possible to encounter a field intensity which exceeds 5×10^4 and even 10^5 V/m. /66

Influence of electrical forces on freezing of supercooled droplets. In many works, it has been shown that the probability of droplet freezing depends on the magnitude of the electrical field. Pruppacher [139] suggested that the increase in the crystallization probability is connected with the penetration of crystallization nuclei into water. These nuclei either develop during discharge in an electrical field or exist in the air surrounding a droplet and are transferred to it by electrical forces. In contrast to this idea, Loeb [123] suggested that the freezing begins if the electrical forces are great enough to break down the surface of the droplet and to draw from it filaments of water about 10^{-6} cm thick. Water formations of such size, most likely oriented along the pole, are liquid crystals which can act as crystallization nuclei. Recent investigations [123] have shown that the viewpoint of Loeb is justified. Gabarashvili and Kartsivadze [106] noted that the crystallization process takes place in different ways in positively and negatively charged droplets. A significant increase in the crystallization probability is produced with a field intensity at the surface of the drop approximately equal to 10^6 V/m. This field intensity may also develop with large charges of the droplets when the droplets converge in external fields, or when droplets which have relatively small charges converge in zones of cloud inhomogeneities — or merely in their external field. A drop in the crystallization temperature in the electrical field is most effective at the lowest temperatures.

Hence, in the supercooled zone of clouds and in zones of electrical inhomogeneities, electrical forces can considerably accelerate the crystallization process, which will necessarily lead to an increase in the condensation

processes of droplet growth, increasing coagulation in turn. This process may be accompanied by a growth of the electrical field in the cloud, which will contribute to intensification of the process, as long as the growth of the field is not limited by the factors discussed above.

Unfortunately, we still do not have a satisfactory theory or information about the state of clouds which would make it possible to calculate both the constants which characterize the kinetics of the growth of individual particles (several estimates of this kind have been set forth in the following section) as well as the development of the entire cloud.

It is clear from the above, however, that such calculations must be based particularly on information regarding electricity in clouds, involving both the average characteristics and the electrical characteristics of inhomogeneity zones.

CHAPTER III

POSSIBILITY OF CONTROLLING THE DEVELOPMENT OF CLOUDS BY ELECTRICAL METHODS

As we pointed out in the preceding chapter, ideas regarding the effect of electrical forces on the development of clouds were expressed a long time ago, and it is no surprise that in the first quarter of the twentieth century experiments were conducted both in the USSR and the USA [24, 25] concerning the influence on clouds of seeding with electrified sand. However, the experiments did not yield any positive results, and were therefore suspended.

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In recent years, in conjunction with general expansion of studies on influencing clouds, there has been a slight increase in interest in using electrical forces to influence clouds and fogs. There are even reports on attempts to control the processes of cloud electrification, including processes that lead to thunderstorms [12]. However, no definite results that could be used to formulate any kind of practical recommendations were obtained [90]. Therefore, we will limit ourselves to presenting physical ideas which may be used as the basis of mechanisms for acting on the electrical processes in clouds or changes in the development of clouds, using electrical methods, and we will also discuss briefly the possibility of their realization. We must keep in mind that, together with the possibility of using the methods which will be discussed below in practice, we can significantly clarify the mechanism of cloud development.

§1. Influence of Electrical Methods on Nonelectrical Cloud Characteristics

In Chapter II, we saw how electrical forces could affect the pattern of natural cloud development. It is obvious that we should try to find out how and in what fashion we could successfully influence the development of clouds by changing their electrical state, within the limits of modern technical possibilities. The process of cloud or fog development may be divided roughly into two stages. In the first stage, there is formation of cloud particles with condensation or sublimation of water vapor, and there is evaporation of the particles that are formed, which impedes the former. In the second stage, the cloud particles grow and change into precipitation particles, either as the result of direct coagulation or due to their intensive growth with partial crystallization, which is accompanied by vigorous distillation of the vapor, with liquid particles being changed to solid ones and with subsequent coagulation. The increase in the size and number of particles is counteracted by the evaporation of cloud particles or their fall from the cloud.

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It is obvious that, by forcing the first elements of the processes, it will be possible to succeed with what is called cloud development and by stimulating the second elements of the process, the breakdown of the cloud.

Use of electrical methods to influence condensation processes. Since the time of Thompson (for example, [8]), it has been known that the existence of an electrical charge q on a particle with a radius r reduces the vapor pressure above it. This reduction is proportional in the first approximation to q^2/r . The magnitude of this reduction for particles measuring more than 10^{-6} cm (10^{-2} microns) is so small that it can be used for stimulating condensation processes only by activation of condensation nuclei which already exist. On the other hand, the number of nuclei sufficient for cloud formation usually exists in the atmosphere (see, for example, [6]). Hence, this method may find very limited use in zones where there are aerosols but there are insufficient condensation nuclei.

Influence of electrical methods on the crystallization processes in

clouds. It was mentioned in Chapter II that the development of an electrical field on the surface of a particle increases the probability of crystallization due to the elevation of the freezing point [139, 106, 129]. The values of the required field intensity in this case are in excess of 10^6 V/m. Hence, there is a theoretical possibility of influencing the development of supercooled clouds.

There are two ways of putting these methods into practice. First of all, a strong electrical field can be created in a large portion of the cloud. It is necessary to keep in mind, however, that the probability of freezing depends not only on the size of the active field, but also on the time of its application. Hence, it is impossible for an aircraft or a rocket to pass through the cloud, causing a strong electrical field, and thereby to influence a relatively large volume of the cloud. This version of the method is therefore technically /69 difficult to accomplish. However, in those cases when strong electrical fields are formed as the result of some influence on a supercooled portion of the cloud, their influence on the crystallization of the particles may be included in the integral effect of the action.

A second way of influencing the cloud is strong charging of the particles of supercooled clouds. This type of charging can be accomplished in several ways. For example, a body which creates a corona discharge can be passed through the cloud or the cloud can be charged with an ion flux running from the surface of the Earth [96]. The drops may also be charged with a nonelectrical influence on the clouds, and thus make a contribution to the total effect of the treatment.

It is necessary, however, to keep in mind that in those cases when the action leads to a rough regulation of the size of the cloud particles in the supercooled cloud or fog, there are powerful rivals to this method. Known methods of influencing supercooled clouds by injecting dry ice or substances that are isomorphic to ice are quite simple and effective, so that in the near future the electrical methods will no longer be a source of competition for

them. This is particularly valid, since in the temperature range from 0 to -5°C (where the existing methods are unsuited) even the electrical method must be rated very ineffective.

Influence of electrical methods on the coagulation of particles in clouds.

It is technically difficult to change the structure of a warm cloud, by altering in its large volumes the conditions for collision and coagulation of drops, and producing in it a long-acting, powerful electrical field with an intensity of approximately $10^4 - 10^5$ V/m. Such attempts have been made in fogs, making use of the fact that a zone of powerful electrical fields can be created on the path of an advective fog, and in a radiational fog it is possible to shift the source of the field relatively slowly. The action of the electrical field on the coagulation processes may also be a byproduct of nonelectrical methods.

The influence of electrical characteristics of particles on the coagulation conditions may be used not only for dispersing, but also for stabilization of fogs. If the droplets of fog are charged in the same fashion, then, as we noticed earlier, the probability of their coagulation is reduced. It is necessary to note, however, that the electrical field that develops throughout the cloud may again lead to an increase in the probability of coagulation of the droplets as the latter grows.

Stimulation of rain may be achieved with greater effectiveness through increasing coagulation by introducing particles of charged water or other reagents into the upper part of the cloud. Let us look in greater detail at the conditions for this method.

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Engagement of particles in a cloud may be achieved by stimulating gravitational coagulation through the transport of particles of noncharged atomized water into the upper part of the cloud. However, the initial radius R_0 of the reagent particles must be great, on the order of 30 microns, because only with reagent particles are this size can the capture coefficient E of cloud particles (radius 6-10 microns) have a tangible value (Table 3.1) [66].

TABLE 3.1. VALUES OF COEFFICIENT OF COLLISION FOR DROPS WITH RADIUS R AND r WITH $\gamma = 1.7 \cdot 10^{-4}$ POISE, $\rho = 1 \text{ g/cm}^3$, $g = 980 \text{ cm/sec}^2$

r/R	R μ		
	30	25	20
0.2	0.019	—	—
0.3	0.36	0.03	—
0.4	0.71	0.29	$< 10^{-4}$
0.6	1.2	0.65	$\sim 10^{-4}$

Due to the large value of R_0 , the consumption of reagent is very high. Reducing the initial size of the reagent particles and making it possible for them to increase in size to R_0 more rapidly is also the purpose of using electrical forces in methods of this kind. The latter may be achieved by a sharp increase in the capture coefficient E for the capture of cloud particles by the reagent particle by supplying it a high electrical charge.

A particle that carries a charge will gradually lose it, due to the electrical conductivity of the air. Therefore, the time during which a reagent particle will reach a radius R_0 is much shorter than the time in which a significant fraction of the charge is lost. This limitation on the time of reagent particle growth is an important characteristic of the method using electrical charges.

Table 3.2 presents the values of the time T during which a charge on a particle will be reduced by approximately a factor of 3 if the particle is in a cloudless atmosphere.

TABLE 3.2. TIME (T) REQUIRED FOR CHARGE ON PARTICLES TO DECREASE APPROXIMATELY BY A FACTOR OF 3 IF THE PARTICLE IS IN A CLOUDLESS ATMOSPHERE.

H км	0	1	2	3	4	5	6	7	8
T sec. . . .	800	500	300	200	150	100	90	70	60

In clouds, the electrical conductivity of the air is several times less than in the atmosphere at the same level, so that the loss time for the charge is correspondingly greater. Thus, for example, T may be about 1000 seconds at an altitude of 3 - 5 kilometers in clouds.

Hence, in about 1000 seconds, a particle introduced into a cloud will increase to such a size at which the mechanism of gravitational coagulation will begin to act effectively.

Let us see how this requirement is satisfied.

The growth of reagent particle may be calculated by general methods. The latter are presented in monographs by B. Mason [5] and N. S. Shishkin [11], substituting E equal f (R, r, Q, q), where R and r are the radii of the particles of the reagent and the cloud, and Q and q are their charges. When the reagent particle is dropped into a drop-like cloud in which there are no ascending currents and where we can disregard the action of turbulence on the process in question, the time for a particle to increase from the initial radius R_1 to R_0 is determined by the expression

$$t = \frac{3}{\pi} \int_{R_1}^{R_0} \frac{dR}{\int_0^{\infty} E f(r) r^3 (V_R - v_r) dr}, \quad (3.1)$$

where $f(r)$ — is a function of the distribution of cloud particles by size and V_r and v_r — are the rates of fall of the reagent and cloud particles.

A solution of this type encounters considerable difficulties. First of all, we do not know function E in the analytical form. The numerical calculations of E have been performed by several authors [59, 60, 64, 66, 98, 148, etc.] for special cases, and apparently there is a need for an experimental verification of the results of the calculations. However, even if it were

possible to calculate t in some fashion, the assumption made regarding the absence of turbulence and ascending currents for calculating the interaction of the particles which have small rates of fall (1-10 cm per sec) would make the results of the calculation a very rough approximation to reality. In fact, rough estimates of this kind are valuable only for estimating the prospects for continuing work in a given direction.

Calculation of t is considerably simplified if we assume that the cloud into which the reagent particle is thrown is monodispersed, and the rate of fall of the particles is calculated according to Stokes: $V = k^2$, where k is the coefficient of proportionality, and r is the radius of the particle. In this case

$$t = \sum_{i=1}^n \Delta t_i, \quad (3.2)$$

$$\Delta t_i = \frac{4\rho}{k W \bar{E}_i} \int_{R_i}^{R_{i+1}} \frac{dR}{R^2 - r^2}. \quad (3.3) \quad \underline{/72}$$

In these expressions, ρ is the density of the water in the cloud, W is the water content of the cloud, \bar{E}_i is the average value of the capture coefficient for the capture of cloud particles by the reagent particles which vary in size from R_i to R_{i+1} .

After taking the integral, we obtain a formula for calculation of Δt_i :

$$\Delta t_i = \frac{2\rho}{k W \bar{E}_i r} \ln \frac{R_i + r}{R_{i+1} + r} \cdot \frac{R_{i+1} - r}{R_i - r}. \quad (3.4)$$

Let us estimate the growth time for a reagent particle (increase in radius from 10 to 30 microns), if a reagent is dropped into a monodispersed cloud with a particle radius of 7 microns. In the range of $R \approx 10$ to 20 microns, under the condition that the reagent particle is charged at the initial moment

of time ($R = 10$ microns) to a certain limiting charge (i.e., the charge at which breakdown of the air on the surface of the drop begins) the value of the capture coefficient changes from several tenths of a unit to units, and in the range $R \approx 20$ to 30 microns — from several units to tenths of a unit [59, 66, 60, 98, 148]. In accordance with this, the calculation of t is performed for $E_1 = 50, 25, 5$ and $E_2 = 5, 2.5, 0.5$. The results of the calculation are presented in Table 3.3, where the values of t are rounded off to hundreds of seconds.

TABLE 3.3. GROWTH TIME FOR REAGENT PARTICLE FALLING FREELY IN A CLOUD TO INCREASE FROM $R_1 = 10$ MICRONS TO $R_2 = 20$ MICRONS AND FROM $R_2 = 20$ MICRONS TO $R_3 = 30$ MICRONS AS A FUNCTION OF E AND W .

$\frac{W}{g/m^3}$	$R \sim 10-20 \mu$		$R \sim 20-30 \mu$		$t = \Delta t_1 + \Delta t_2 \text{ sec}$
	E_1	$\Delta t_1 \text{ sec}$	E_2	$\Delta t_2 \text{ sec}$	
0.3	50	200	5	400	600
	25	300	2.5	800	1100
	5	1500	0.5	4000	5500
0.5	50	100	5	200	300
	25	200	2.5	500	700
	5	900	0.5	2400	3300
1	50	50	5	100	200
	25	100	2.5	200	300
	5	500	0.5	1200	1700
2	50	20	5	60	100
	25	50	2.5	100	200
	5	200	0.5	600	800

The value of the capture coefficient E is largely dependent on the charge on the reagent particles and the ratio of the sizes of cloud and reagent particles. Relatively small changes in this parameter may lead to a considerable reduction of E (Table 3.4) and a sharp increase in Δt , which nullifies the effectiveness of the action. This is why the use of electrical forces in warm clouds encounters considerable technical difficulties. However, the calculation results indicate that it is advantageous to look for practical solutions

for using these methods on warm clouds, having a water content of about 1 g/m^3 or more.

TABLE 3.4. CAPTURE COEFFICIENT E AS A FUNCTION OF R_1 ; r; Q; q = 0 [58a]; $R_1 = 10$ MICRONS.

Drop radius	Q, CGS		
	10^{-5}	$5 \cdot 10^{-5}$	10^{-4}
$r = 8 \mu$	13,59	52,66	93,53
$r = 6 \mu$	7,235	29,51	53,17

Let us determine the amount of reagent required for effective elution of a cloud. With the same determination of the capture coefficient, the condition for total elution of a cloud may be written as follows:

$$n E \pi R^2 = 1, \quad (3.5)$$

where n — is the number of reagent particles in 1 cm^2 ; R — is the particle radius.

Let us assume that there is a stratiform warm cloud with a thickness $Z = 2 \text{ km}$, having a water content of 1 g/m^3 . The tentative value of E is 0.5 when reagent particles with a radius 30-100 microns interact with particles having a radius of 6 to 8 microns (Table A.3 in [5]). The growth of the reagent particle radius is evaluated according to the formula

$$\Delta R = \frac{E W Z}{4\rho}. \quad (3.6)$$

Assuming that the growth of the reagent particles from 10 to 30 microns takes place within a small area of the cloud height, we will find that ΔR equals 200 microns, after substituting the assumed values of Z , E , W , ρ in Formula (3.6).

Let us discuss the problem of achieving complete elution of the cloud from an altitude of $Z' = 1.5$ km. At this latitude, $R = 60$ microns, and if $E = 0.5$, $n = 2.6 \times 10^4 \text{ cm}^{-2}$. The reagent consumption at $\rho = 1 \text{ g/cm}^3$ is about 1 gr/m^2 . If this is done from an aircraft moving at a rate of 300 km/hour, /74 and the width of the frontal effect is 50 m, then in 1 second it will be possible to seed an area approximately equal to 4000 m^2 . Hence, when treating a cloud with this water content and structure for 1 second, it is necessary to discharge 4 kg of reagent broken down into droplets with a radius of 10 microns, charged to their limit. For droplets with a radius of 10 microns, the limiting charge is about $3 \times 10^{-4} \text{ C}$. Since the total number of charged particles must be about 10^{12} , the current which charges the particles must be about $3 \times 10^{-2} \text{ A}$. It is obvious that, in conjunction with the considerable reagent consumption, the method under consideration may only be used in special situations when there is a severe need to remove a cloud cover above certain areas. In addition, there are also other difficulties (see below). It should be kept in mind that the cloud is a process which frequently is unstable, and whose direction may often be changed by relatively simple methods. The fall of precipitation, for example, changes the airflows in the vicinity of the cloud to some degree, the conditions for transport of moisture, etc. Therefore, stimulation of precipitation may cause further intensification. An evaluation of these consequences, however, exceeds the framework of the considerations presented above. In describing the results, it is necessary to keep in mind the increase in the electrical fields, both average and extreme, and the charges on the particles that develop in the clouds following the beginning of precipitation as well as the influence of electrical characteristics on the enlargement of particles.

The treatment of a warm cumulus cloud lends itself to calculation to a still lesser degree. Convective clouds represent such an unstable colloidal system that only a slight intervention is usually required during their natural development in order to produce precipitation. Obviously, the use of electrically charged water spray or electrically charged, giant hygroscopic condensation nuclei is more effective than the use of uncharged reagents.

Everything we have said above concerning the treatment of warm clouds theoretically applies to treating warm fogs. However, due to the reduced thickness of fogs, the reagent consumption for seeding them must be greater. An unusual idea about reducing the consumption of reagent and increasing its effectiveness was proposed by A. D. Solov'yev [76]. He recommends that electrified bubbles be used as a reagent, similar to ordinary soap bubbles. The use of these bubbles, similar to ordinary soap bubbles be used as a reagent. The use considerably reduce the amount of reagent required for elution. No reports on the results of using this method in practice were given.

Let us examine the results of experimental tests of these principles. /75

Increasing the action of electrified droplets of reagents in comparison to nonelectrified ones was mentioned by N. Vager [23], who studied the dispersal of artificial fog in chambers.

Electrified drops used for dispersing fogs have been employed in laboratory experiments by L. Demon and M. Vadell [99, 165]. The results of their experiments were qualitatively the same as those obtained by N. Vager.

L. Demon [99] attempted to disperse fog under natural conditions by using highly electrified droplets generated by sprayers mounted on the ground and also to scatter warm cumulus clouds in good weather by scattering electrified droplets generated by sprayers aboard an aircraft. His experiments were not successful. In the first case, as he reports, the corona discharges from pointed objects, excited by the space charge of the droplets, discharged them to a considerable extent, which prevented the effective action of the droplets on the fog. A similar phenomenon was observed aboard the aircraft, but the scattering of the droplets from the aircraft was hindered by electrical forces which developed between the aircraft (which acquired a charge due to ejection of a cloud of charged droplets) and this cloud of droplets. The results of the work of L. Demon obviously must be kept in mind when organizing similar experiments.

Attempts have been made to disperse fog by precipitating it in an artificially produced electrical field [12], as well as by stimulating the merging of fog droplets as they move near a high-voltage wire [12]. No information is given regarding the results of tests of these theories.

There are reports describing a test to disperse fog by means of a device consisting of a nylon net mounted on a truck. Apparently, the droplets of fog strike the net as the vehicle moves along. The droplets are strongly electrified, and the process of electrostatic coagulation begins with subsequent precipitation of the droplets.

We would like to mention one more method of charging cloud droplets in order to increase coagulation, which was done in Australia. An aircraft carried a long tail made of wires that produced a corona which was supposed to charge the droplets with subsequent growth of the latter to the size of precipitation particles. Unfortunately, these experiments were not completed.

Quite recently, using long corona-producing lines mounted on the ground, an attempt was made to alter the coagulation conditions by artificial charging of cumulus clouds [96]. Apparently, it was expected that the effectiveness of droplets merging in the clouds would be increased, and the precipitation would increase after this. The amount of precipitation that fell on the leeward and /76 windward sides of the corona-producing lines was measured. No differences could be found, although the disturbance in the potential gradient of the electrical field of the atmosphere on the ground was measured at a distance of 10 km on the leeward side of the line. Here an increase in the radar reflectivity was found. The authors of [96] suggest that the charging of the droplets promoted their coagulation and the appearance of large droplets in the clouds, but their premature precipitation stopped the growth of the clouds.

Hence, we still do not have any reliable information on the results of treating warm clouds or fog under natural conditions using electrical forces,

and the positive results of the experiments are confined to a series of successful laboratory tests. However, the possible application of these methods is being subjected to considerable study.

§ 2. Methods of Changing the Electrical State of Clouds

Experiments on changing the electrical state of clouds have at least four purposes. First of all, they can be used to study the physics of the cloud electrification process and the relationship of the electrical characteristics of the clouds to other characteristics. Secondly, they not only allow improved weather forecasting, but also make it possible to evaluate the conditions for development of radio interference in clouds as an aircraft or lighter-than-air vehicle is passing through them, etc. In the third place, they can help protect particularly sensitive objects on the ground against thunderstorms (forests, asphalt, lakes, regions where explosions are being set off, etc.). In the fourth place, in the distant future they may serve for removing from the atmosphere pollution.

Existing methods of changing the state of clouds can be divided into two classes: electrical and nonelectrical.

Electrical methods can be subdivided into two groups: active and passive. The first group consists of methods in which electrical charges are introduced in some fashion; the second consists of methods in which the electrical losses are altered in some fashion, so that at a given intensity the cloud electrification process leads to a change in the electrical state of the latter.

It is also possible to use this method of generating unipolar currents by means of corona-producing electrodes to charge clouds [96, 167]. The space charge which is produced as the result of corona-production is carried into the cloud by ascending air currents. When the apparatus is installed in the

mountains, the space charge may be injected directly into the cloud. The droplets of the cloud, which act like a filter, capture the space charge from the incoming air.

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In order that the space charges from the apparatus may enter the cloud, and that the current density charging the latter may be sufficiently great, the apparatus must either be designed as to cover a sufficiently large surface, or erect a device for aiming the charged stream, or finally, the equipment must be placed directly in the cloud.

In the experiments performed by the Leningrad Institute of Experimental Meteorology in the mid-1930's under the direction and with the participation of S. N. Tokmachev, V. V. Bazilevich, B. V. Kiryukhin, V. Ya. Nikandrov et al. [20], it was possible to effectively charge relatively large volumes of fog, mounting the corona-producing electrodes directly in the fog. The investigators also observed the positive effect of such charging on the coagulation of fog droplets. In many cases, they observed precipitation of droplets and dispersal of fog within a radius of 20 m from their installation. It is necessary to mention the pioneering nature of this work carried out by the Leningrad Institute of Experimental Meteorology, both in connection with the ideas proposed for treating natural fogs and in connection with the methods employed.

The effect of corona-producing lines on the fog charging was also mentioned by J. Chalmers [14], who established that fog on the windward side of a high-voltage line was intensively charged, although the distance from the line was several kilometers.

Apparatus for artificial charging of clouds was developed by B. Vonnegut and C. Muir. In one of their experiments, they used a wire 0.025 cm in diameter, 7 km long, on which they produced a charge of 25 kV. The corona-producing current from the wire reached 1-2 mA and depended on the direction

and force of the wind. At a distance of 8 km from the line, the electrical field on the ground, due to the charges generated by the line, still had a sign which was opposite to the normal field.

Vonnegut and Muir considered it possible to use this apparatus to regulate the thunderstorm danger of a cloud by changing its initial charge. They suggested that organized electrification — i.e., the only process of electrification mentioned thus far, affecting the entire cloud as a whole — would begin in the Cu and Cu cong stages. On the basis of this statement, the theory, known by the name of the convective mechanism of cloud electrification, was subjected to serious criticism at the Third Conference on Atmospheric Electricity in Montres [13], and at the present time cannot be considered as having any foundation at all. The studies mentioned above which were conducted at the Main Physical Observatory [39, 83], showed that electrification of clouds at the Cu or Cu cong stage had little influence on the appearance of charges /78 in the Cb stage. However, the results of the experiments performed by Vonnegut and Muir supported the possibility of artificial electrification of clouds.

For a more effective transport of the space charge into the cloud, S. Colgate used an enormous polyethylene tube, 350 m long, kept straight and supported by a flow of charged air, which was pumped in by a very powerful fan [161].

The charging current of the cloud which was produced by the experimental apparatus reached 1 mA, i.e., it was equal to a "good weather" current, flowing into an area of about 1000 km^2 .

Currents of appreciable magnitude may also flow into a cloud from electrodes that are raised into the cloud on captive balloons. In this case, the source powering the electrodes may be the electrical field of the atmosphere. The current which flows from such an apparatus will depend both on the applied voltage and on the speed of the air current blowing over the electrodes.

Let us look at the existing passive methods of changing the electrical state of clouds.

G. Wakeman [168] suggested reducing the electrical activity of a thunderstorm cloud and even preventing the development of lightning in it by increasing the electrical losses in the cloud. For this purpose, he suggested that a large quantity of needles be thrown into a cloud in which considerable electrical fields had already developed (in particular, he wanted to use chaff and straw). On entering a strong field, the needles begin to give off a corona, which increases the electrical conductivity of the air and, therefore, reduces the intensity of charge accumulation in the cloud, reducing the probability of lightning generation.

Individual sharp needles 10 cm long begin to give off a corona in a field with a strength of 25-30 kV/m. In a 70 kV/m field, the corona current increases to 10^{-4} A. In order to prevent a thunderstorm discharge, it is necessary, according to the estimates of H. Kasemir [120], that the current of the corona produced by all of the needles introduced into the cloud amount to about 1 A. In the opinion of Kasemir, this would require that about 10^6 needles be thrown into a small cloud (1 needle for a volume of 10^4 m^3). Since 5000 needles weigh about 1 kg, it will be necessary to throw about 200 kg of needles (straws). It should be mentioned that estimates of the effectiveness of these needles used by Wakeman and Kasemir are considerably overestimated. In particular, they did not take the fact into account that the conductivity in thunderstorm clouds is high. For effective protection, all of the needles would have to produce (as we have seen) a current, not of 1 A, but about 100 A, i.e., one would need, not 10^6 , but 10^8 needles with a total weight of about 20,000 kg. In addition, the authors of these papers failed to take into account the losses of ions producing conductivity during their capture by droplets and the role of turbulence in the cloud, displacing the positive and negative charges generated by the needles (we should recall that one needle 10 cm long is needed for a volume of about $10^3 - 10^4 \text{ m}^3$), as well as the role of

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recombination of ions, reducing the number of ions producing conductivity. Therefore, it is necessary to increase the number of needles still further and the total weight required for effective treatment could reach 100 tons or more.

The experiments of Kasemir in treating clouds have not yet led to any definite results [120].

By producing instantaneous elongated areas above the zone of high conductivity beneath thunderstorm clouds, it has been possible to produce and direct lightning discharges along them. In particular, lightning discharges have been observed in high (up to 100 m) water columns raised by powerful explosions and in long wires carried by rockets [73].

We mentioned earlier that a charged aircraft under certain conditions may provoke a lightning discharge in a cloud [2].

Thus far, we have been talking about clouds. But we cannot omit the possibility of cleaning the atmosphere of pollutants by electrical means. Small uncharged particles of pollution settle on the ground under the force of gravity. However, when there is one elementary charge on a particle measuring 10^{-6} cm, located in an electrical field with an intensity of $E = 1$ V/cm (normal value for the field strength of the atmosphere at the surface of the ground), the ratio of the forces of gravity to the electrical forces mg/eE amounts to 10^{-3} . This means that the existing electrical fields might play an important role in purifying the atmosphere of contaminating impurities in some fashion. In dealing with this problem, V. Shaeffer [162] noted that it is possible to stimulate purification of the atmosphere by artificially charging in some fashion the industrial nuclei that enter the atmosphere. Their danger (in addition to the other problems which exist) lies in overseeding the atmosphere with condensation nuclei, which consequently may lead to the appearance of drought.

Nonelectrical methods. The relationship between electrical and other processes in clouds has made it possible to change the electrical state of clouds by treating them with certain reagents such as carbon dioxide, surfactants, substances which are similar to ice, etc. If precipitation falls as the result of this treatment, the electrical characteristics of the clouds will be more pronounced, but if the cloud breaks up after being subjected to this treatment, the electrical characteristics of the clouds will become less pronounced.

For example, let us look at Figure 3.1, in which we have shown the change in the electrical field of a cumulus congestus cloud after treatment with several kg of solid carbon dioxide [40]. As we can see, only a few minutes after this, the process of organized electrification has begun in the cloud, coinciding in time with the development of large droplets in the cloud.

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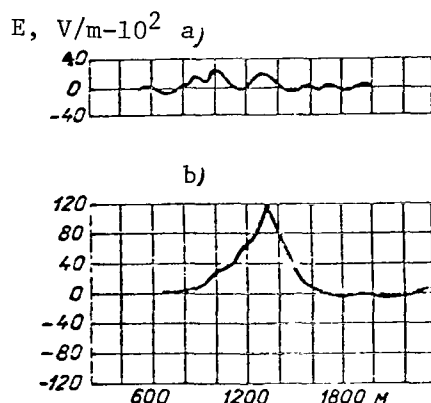


Figure 3.1. Potential gradient E of an electrical field in cumulus congestus cloud before treatment (a) and after treatment (b).

Figure 3.2 shows the results of measuring the potential gradient of an electrical field in the atmosphere in the vicinity of a cumulus congestus cloud before and after treatment with iodine compounds of lead and silver in a pyrotechnical composition, which led to precipitation [83]. Organized electrification took place 14 minutes after the seeding.

In 1969, the problem of controlling the thunderstorm danger of clouds was considered by Stow [155]. He feels that excessive seeding with ice-forming

reagents in large convective clouds, which are in a development stage preceding the stage of maturity, may prevent or reduce the electrical activity of the cloud for the following reasons: first of all, the convective currents which

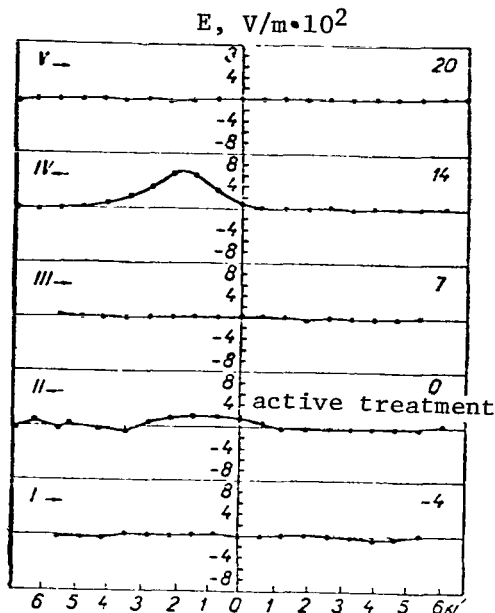


Figure 3.2. Vertical component of potential gradient E of electrical field of the atmosphere after treating Cu cong. Area of influence: 125 km SE of Tallin, 14 August 1969; flight altitude 4.7 km, airspeed approximately 240 km/hr. I, II, III, IV, V - numbers of passes of the aircraft above the cloud along the same course with bearings ϕ , $\phi + 180^\circ$

Abscissa: distance from cloud. Treatment performed when crossing near edge of cloud on second pass. On the right side of the graph is the time (in minutes), counted from the time of treatment. Arrow shows direction of aircraft movement.

are caused by the liberation of latent heat during freezing of the supercooled droplets may cause the appearance of turbulence, as the result of which fresh cold batches of air will enter the cloud and prevent its growth, and consequently will prevent the change of the cumulus congestus cloud into a thunderstorm cloud. Secondly, excessive seeding leads to a sharp decrease in the amount of supercooled water in the cloud, which will reduce the effectiveness of one of the principal (in the author's opinion) mechanisms for the formation of thunderstorm electricity — electrification caused by the collision of ice crystals with hail. In the third place, the size of the particles is reduced, and so is their dispersion in the cloud. On the one hand, this will reduce the probability of freezing droplets exploding, and thereby reduce the effectiveness of the treatment, accompanying the droplet electrification mechanism. On the other hand, it will reduce the probability of collision of cloud particles due to which the induction mechanism of electrification will be impeded.

In this system of treating clouds that are likely to turn into thunder clouds, regardless of the apparent effectiveness, there are still a number of weak points. First of all, there are no criteria for determining whether a cloud is in danger of turning into a thunderstorm cloud, and it is practically impossible to treat all "suspicious" clouds that might turn into thunderstorms. Secondly, clouds which are in the stage of transition from Cu cong to Cb are usually part of such a powerful developing system that it is very problematical as to whether it is possible to artificially change the dynamics of cloud development by such measures. New quantities of heat and moisture which are accumulated rapidly may nullify the inhibition of cloud development produced by the methods of Stow. Problems of regulating the thunderstorm danger of cumulus congestus clouds require further theoretical treatment. /81

The experiments of L. Battan [94], in which the idea of seeding convective clouds with silver iodide was employed, did not lead to any definite results.

Another group of methods for regulating the electrical state of clouds is based on a change in the effectiveness of electrification of cloud particles and precipitation particles. If electrification depends to a large degree on the physical and chemical composition of the particles, negligible changes in the composition of the particles or the condition of their surfaces may have a considerable influence on cloud electricity. /82

Thus, one of the powerful electrification mechanisms, as we pointed out in Chapter II, is the generation of charges during freezing of water (the Workman-Reynolds mechanism, which takes place during the explosion of freezing supercooled droplets, in the separation of water from melting hail, etc.). Usually, regardless of the type of impurity contained in the water, this kind of separation means that the ice particles are charged negatively, and water particles are charged positively. Only one impurity (ammonium) has the opposite effect. E. Workman [27] suggests that, by adding ammonium to the cloud, the sign of the cloud dipole could be reversed. It is obvious that by choosing

the appropriate quantity of ammonia one could try to achieve the absence of appreciable electrical fields in a cumulonimbus cloud. It would then be necessary to solve the very difficult problem of mixing the reagent material with the cloud water, and in the correctly selected proportions.

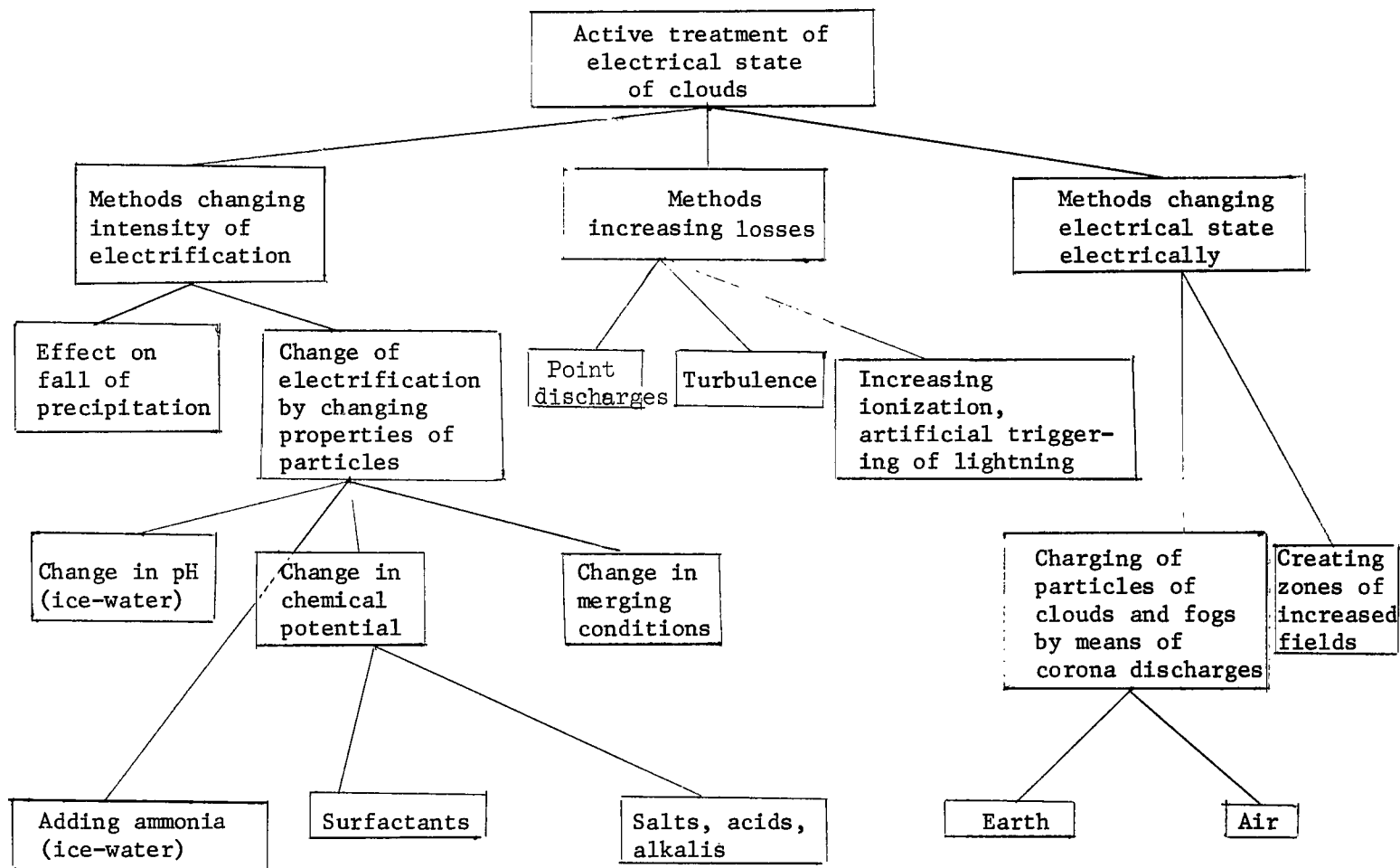
In a similar fashion, one could try to change the electrification conditions of clouds (as proposed by L. G. Kachurin et al. [55]) by treating the chemical composition of the droplets in the zone where they can explode when supercooled. According to the data in this paper, electrification of exploding droplets depends to a large extent on the pH of the water; it decreases with deviation of the pH to either side from certain optimum values. Consequently, introduction of acids or alkalis (when the process in question is active enough) could change the electrical state of the cloud if, of course, it is known how to add the necessary substances to the drops. The quantity required for the cloud will not exceed tens of kilograms. In any case, experiments of this kind will make it possible to determine whether or not this mechanism does in fact play an important role in the electrification of clouds. It is likely that this kind of relationship is also valid for the effect of conductivity of freezing water; its reduction or increase, relative to certain optimum values, may also lead to a decrease in the electrification of the exploding droplets.

Introduction of surfactants into a cloud can also change the intensity of the electrification process, although the sign of such a change is difficult to guess in advance.

Table 3.5 shows suggested methods of active treatment of the electrical state of clouds, which we have gathered from the data and the literature.

In concluding this survey of ideas on controlling the electrical activity of clouds and actively influencing clouds using electrical forces, we must stress the relative abundance of ideas in this area, and the almost complete absence of their technical implementation. At the present time, when many

TABLE 3.5



other problems of actively influencing nature have not been solved, active treatments have not been included in the arsenal of ordinary technical available means, and man is generally adapting himself to the weather rather than changing it, these gaps are not very noticeable and sometimes appear unimportant against the background of the tremendous technical achievements made in recent years. However, in a short time, actively influencing nature will become vitally necessary.

However, the quantity of materials being discharged by man into the atmosphere is increasing ominously. Alkalis and acids, salts and organic compounds are becoming increasingly frequent and increasingly abundant in the water of clouds. If the electrification of clouds really depends on a negligible quantity of chemical impurities, thunderstorm charts may change significantly in connection with industrial activity. Prediction of these changes and regulation of them should be regarded as urgent tasks. An arsenal of ideas and methods must be devised in the laboratory to help solve new problems of actively influencing and regulating the consequences of industrial activity. An important role in this regard is played by methods of regulating cloud electricity and electrical methods of influencing clouds.

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CONCLUSIONS

Data obtained recently, presented in a brief and categorical way which is necessitated by a short survey, have permitted some progress to be made in solving the problems mentioned in the foreword. As is usually the case, the increase in knowledge has made it possible to deviate from many schematic representations, the main advantage of which has been simplicity. The framework of our efforts has been to limit ourselves only to certain problems which touch directly on problems of atmospheric electricity and the relationship between meteorological processes in clouds and their atmospheric-electrical characteristics.

In many cases, studies have led to apparently paradoxical results. It was unexpected that all forms of clouds are generators of electricity. Non-thunderstorm clouds, occupying large areas, may make a significant contribution on the whole to the production of an electrical field in the atmosphere. It was also unexpected that the average currents flowing over thunderstorm clouds would differ by one order of magnitude in different regions. Let us recall that the calculations of the current balance for the entire earth, according to Wilson's system, obtained from data by O. Gish, and J. White, C. Sturgis, etc., were based on the idea that the current from a single thunderstorm is about 0.5-1 A. Even with this assumption, it was found that the current in thunderstorms is scarcely adequate to compensate for "good weather" currents. According to the results of our studies, carried out in the middle latitudes, /85 the current in a thunderstorm amounts to about 0.1-0.2 A in all. It is obvious that, for a correct presentation of the current balance, it is necessary to know the thunderstorm characteristics in various physical-geographic regions. It is most likely that the effect of the underlying surface (for example, various territories and aquatoria) introduces as much diversity into thunderstorm activity as does the change in latitude. Hence, during the coming atmospheric electrical decade, we must solve, first of all, the problem of generation of electricity by clouds of all types in various physical and geographical regions. This problem may be solved through extensive international cooperation.

It is necessary to change significantly the ideas of investigators regarding the electrification mechanisms in clouds in connection with the clarification of the mechanism for charge generation in stratiform clouds, which is unrelated to the capture of air ions, and in conjunction with the observed effect of colossal electrical losses in thunderstorm clouds due to the unexpectedly high effective conductivity in them. Hence, several elementary electrification processes, whose action has usually been used to explain thunderstorm electricity, are not effective enough to produce the processes that take place in thunderstorms. It is necessary to examine a number of

ideas involved in atmospheric electricity and the existence of both positive and negative polarization of all types of clouds. Ideas regarding the important role of fluctuations (both electrical and otherwise) are vital for an understanding of cloud evolution.

In concluding this survey, we would like to mention that we have tried to set forth only the basic facts which are of interest for studying the problems of the relationship between electrical and nonelectrical characteristics of clouds, paying special attention to the electrical structures of clouds. We have intentionally omitted certain questions involving interpretation of phenomena, since the introduction of a discussion would have considerably complicated the presentation of the basic contents of the work, and would have considerably increased its scope. In those works, which have been cited in this survey, the reader will find the viewpoints of various authors concerning the problems discussed. In many cases, however, we have limited ourselves to a presentation of the results of discussions. We feel that in this form the work can be viewed as an introduction to the problems mentioned earlier, and we hope that it will turn out to be valuable for researchers on cloud physics.

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